CONTRACTOR REPORT

PIER
Public Interest Energy Research
CALIFORNIA ENERGY COMMISSION

Environmentally-Preferred Advanced Generation

Durability of Catalytic Combustion Systems

APPENDIX II: RAMD Testing and Control System Development

Gray Davis, *Governor*

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

What follows is the topical report for the Durability of Catalytic Combustion Systems Project, conducted by Catalytica Energy Systems. The report is entitled "**RAMD Testing and Control System Development".** This project contributes to the Environmentally-Preferred Advanced Generation program.

For more information on the PIER Program, please visit the Commission's Web site: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

Catalytica Energy Systems Inc. (CESI) is developing a novel catalytic combustion process that produces ultra-low emissions for natural gas fired turbine engines. As part of this effort, the California Energy Commission sponsored development of supporting technologies and on-grid demonstration of the CESI Xonon® Catalytic Combustion system. This report covers the RAMD (Reliability, Availability, Maintainability, Durability) testing and control system development. The purpose of this project was twofold:

1) To demonstrate the Reliability, Availability, Maintainability and Durability of a Xonon® equipped Kawasaki M1A-13A combustion system

2) To develop control technology to handle severe load transients associated with load application and load shedding (instantaneous unloading of the generator) during on-grid operation

Objectives

The specific project objectives include:

- Accumulate 8,000 hours of on-grid operation with the Xonon® equipped M1A-13A
- Achieve low emission targets for NO_x, CO and unburned hydrocarbons (UHC) while operating at base-load conditions (all values corrected to 15% O_2)
    - NO_x < 3 ppm
    - CO < 5 ppm
    - UHC < 5 ppm
- Demonstrate RAMD of the combustion system
    - Reliability of 98%
    - Availability of 96%
    - Maintainability (no numerical goal)
    - Durability of 100% of design goal
- Demonstrate the control system capability to handle the severe load transient conditions experienced during load application and shedding
- Integrate new technology developments into the combustion system as they become available

Outcomes

- The Xonon® equipped M1A-13A engine achieved 8,128 hours of on-grid, low-emission operation. The goal was to achieve the 8,000+-hour target in continuous operation on the same combustor build. However, due to hardware performance issues, the 8,128 hours were accumulated over the course of two years and four combustor builds. Additionally, some key components were replaced to improve durability and performance. Based on the data collected that validate our model projections, the final combustor build can achieve the 8,000-hour life goal.
- The Xonon® equipped M1A-13A demonstrated average emissions levels below target values at base-load conditions (see Table ES1). Individual 30-minute averaged results for NO_x never exceeded the 3.0 ppm-target value. Early in the test program, on a number of occasions the CO and UHC levels exceeded target (5.0 ppm) and even permit levels (10 ppm). In most cases, these short-term excursions were attributed to on-going controls development work on catalyst and preburner fuel splits. As the testing progressed, the frequency of CO and UHC emissions target excursions decreased dramatically.

	Min	Avg	Max
NOx (ppm)	0.5	1.3	2.9
CO (ppm)	0.0	0.9	94.5
UHC (ppm)	0.0	1.3	9.1

Table ES1 -- RAMD emissions for 8,128 hours of operation (30 minute averages)

- The RAMD of the combustion system was:
  - Reliability was calculated at 99.2%, which exceeded the 98% goal
  - Availability was calculated at 91.2%, which fell short of the 96% goal
  - Maintainability was not quantified because failed components were redesigned rather than being repaired or replaced.
  - Durability was less than 100% due to the early replacement of some key system components for performance and/or durability issues. The actual value for durability was not calculated since the components were replaced with new designs.

  Accurate values for Maintainability and Durability can be determined once the combustion system design is set and run time can be accumulated with this new design.
- The control system modifications improved the stability of the control system to various levels of load application and shedding. Other modifications improved the ability of the system to re-synchronize with the grid after load rejection.

- Several improved designs were created in parallel, non-PIER 1 CESI development programs and were integrated into the combustion system over the duration of the RAMD test program. These improvements include:
    - A new catalyst axial support
    - A catalyst foil pack with enhanced aging characteristics
    - The inclusion of a combustor bypass valve

I. Introduction

Catalytic combustion has been in development for several years at Catalytica Energy Systems Inc. (CESI). Hundreds of hours of rig and simulated engine testing have validated the various design features of the catalytic combustion system. The results from these tests combined with extensive analytical design activities resulted in a fully functional catalytic combustion system capable of meeting the stringent project emissions targets (< 3 ppmv NO_x). The resultant Xonon® 2.0 catalytic combustion system as installed on a Kawasaki M1A-13A gas turbine engine is shown pictorially in Figure 1.1.

Prior to the current program, an earlier configuration of the combustion system (the KHI-1 prototype) had operated in excess of 1,000 hours in testing performed in Tulsa, Oklahoma.

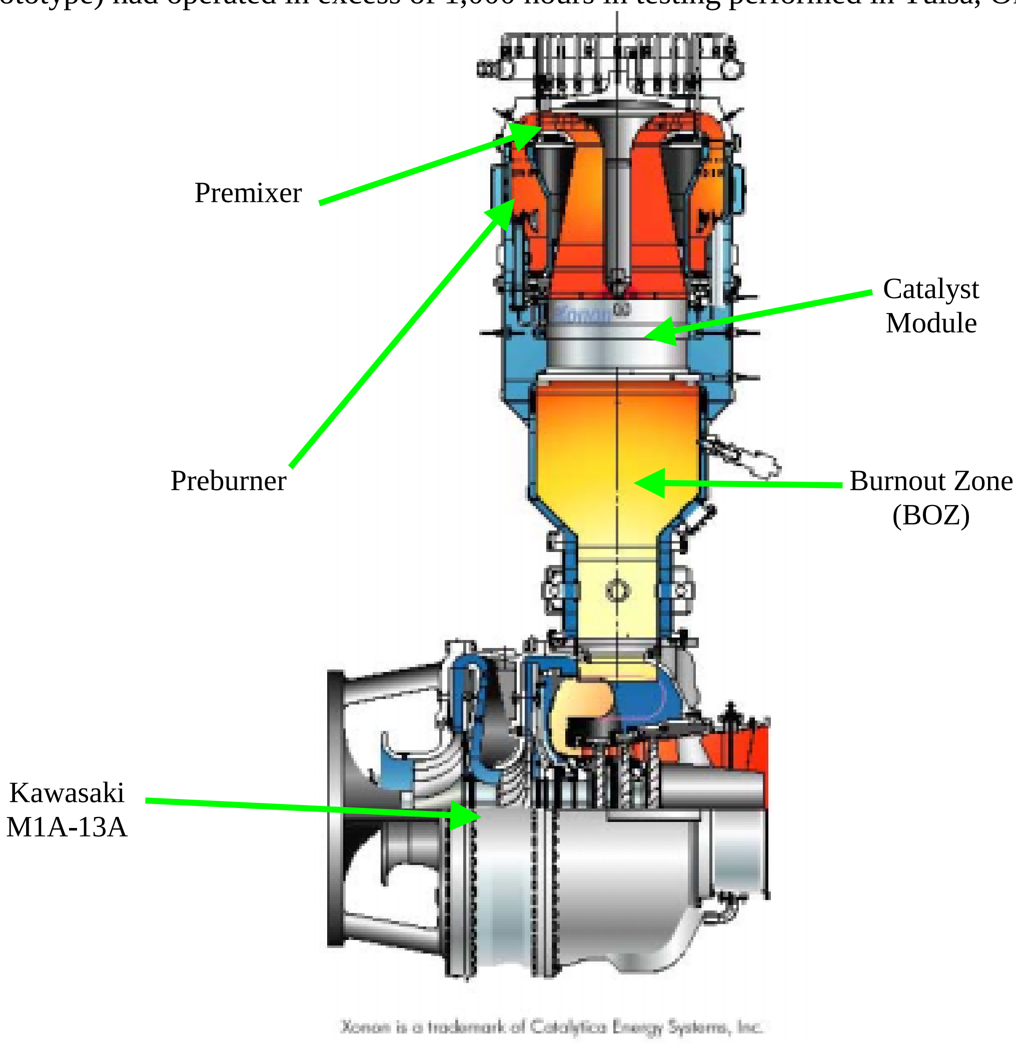


Figure 1.1 – Xonon® 2.0 Catalytic Combustion System installed on Kawasaki M1A-13A Engine

This test provided valuable information regarding the initial durability of the catalyst and other components of the combustion system. The next step towards commercialization was to demonstrate the durability and reliability of the Xonon® 2.0 combustion system, including its ability to operate unattended for an extended period (8,000 hours). The

Xonon® 2.0 combustion system shown in Figure 1.1 consists of a preburner, a fuel/air premixer, a two stage catalyst module and a homogeneous burnout zone. The preburner preheats the air to catalyst operating temperatures. The premixer thoroughly mixes the warm air and fuel prior to entering the catalyst module. In the catalyst module, the fuel air mixture is partially converted in a flameless combustion process. The remaining reaction occurs in the homogeneous burnout zone before the hot product gases enter the turbine.

CESI purchased an M1A-13A Kawasaki gas turbine engine and installed it on a site owned by the Silicon Valley Power (SVP) Company located in the City of Santa Clara (see Figure 1.2). SVP provided financial assistance to the project by providing low cost fuel and reduced rental charges. The power produced was used on site and exported to the local grid. The intent was to exercise the system through a rigorous set of duty cycles consistent with actual industrial operation. This testing covered over 8,000 hours during which the emissions and performance were continuously monitored. In addition, data used to calculate the reliability, availability, maintainability and durability (RAMD) were gathered and analyzed.

Figure 1.2 -- The Xonon® equipped Kawasaki M1A-13A unit installed at SVP

II. Approach

The project is built around a RAMD engine test that is designed to test and demonstrate the durability and reliability of the combustion system. RAMD is an approach designed to quantitatively measure the **R**-reliability, **A**-availability, **M**-maintainability and **D**-durability of a system composed of many components. The durability engine test ran nearly continuously with system failures or stoppages recorded and analyzed. Development efforts, performed in parallel, were initiated as technology improvements. As these technology improvements were developed, they were incorporated into the RAMD engine test during stoppages or when appropriate. Figure 2.1 shows the RAMD project design in a schematic format. The overall project objective was to reach the end of the project with a demonstrated RAMD performance and emissions levels suitable for the target power generation market.

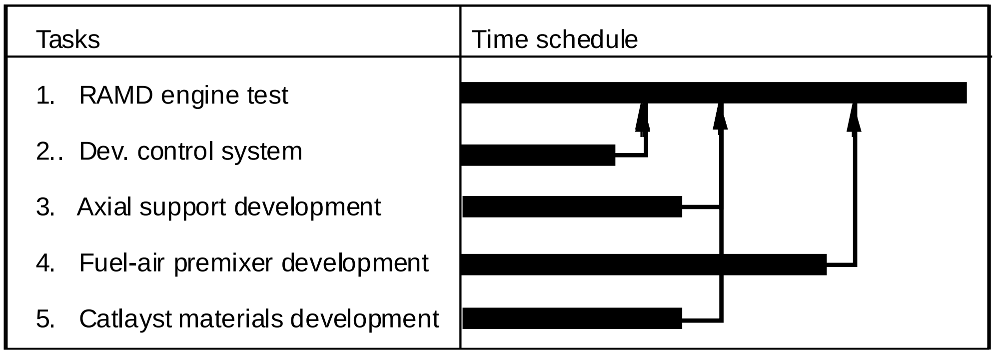


Figure 2.1 -- Schematic overview of the RAMD project design showing testing in parallel with technology development

2.1 Test Bed Selection

Kawasaki Heavy Industries Limited (KHI) produces the rugged M1A-13A 1.5-MW industrial gas turbine which is intended to be packaged as a cogeneration unit producing both electric power and steam (see Figure 2.1.1). It has a modest thermal efficiency of 25.5% (heat rate 13,400 Btu/kW-hr) and is configured with a single external can-type combustor that is readily accessible. The M1A-13A has a pressure ratio of approximately 9.3 to 1; which is comparable to that found in many other industrial gas turbines in the 1 to 6-MW range. The low mass flow (8.2 kg/s) allows the catalytic combustor to be maintained as a small system typical of large rig test units thus reducing the cost of the total system. A low firing temperature of 1004°C makes the engine ideal for catalytic combustion since the modest temperatures in the gas-phase burnout zone (BOZ) allow the use of existing liner cooling technologies.

The M1A-13A engine configuration is an ideal platform for the implementation of the Xonon® catalytic combustion system. The external can combustor configuration does not have the physical size constraints found with other types of combustion systems. This feature allows more flexibility in the size and configuration of the combustion system design. Because of this flexibility, the Xonon® 2.0 catalytic combustion system, although somewhat larger than the original combustion system, is easily adaptable to the M1A-13A engine single-can configuration.

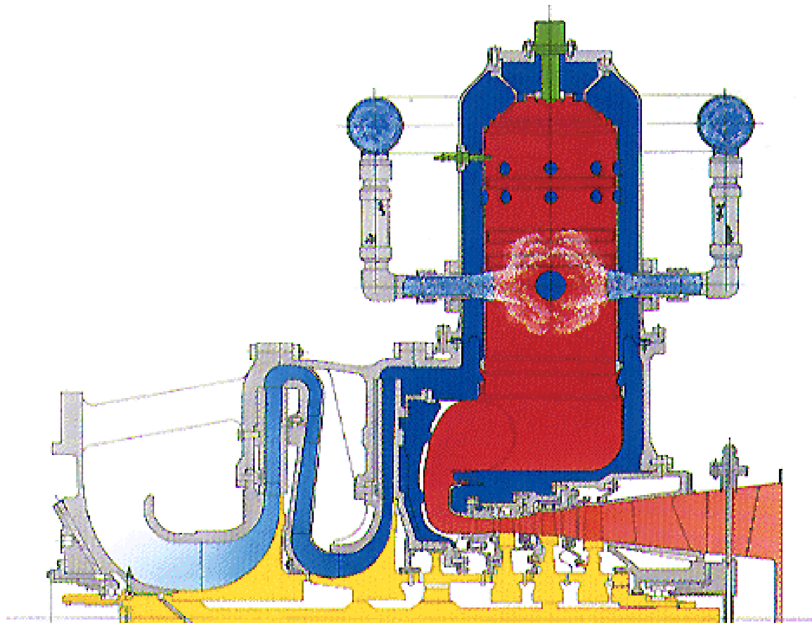


Figure 2.1.1 -- Kawasaki (KHI) M1A-13A gas turbine engine with DLN and water injection

III. Description of Testing Procedures

3.1 Engine Monitoring

The gas turbine exhaust emission levels were monitored at one-second intervals and averaged over the course of 15-minute periods. Oxides of nitrogen (NO_x), carbon monoxide (CO), and unburned hydrocarbons (UHC) were the primary pollutant species monitored and measured. All emissions were verified by an annual relative accuracy test audit (RATA) per federal procedures described by 40CFR60 Appendix B. The species concentrations, expressed as concentration by volume on a dry sample basis [e.g., parts per million by volume, dry (ppmvd)] were measured using the following techniques:

- NO_x: Gas phase chemiluminescence
- CO: Non-dispersive infrared (NDIR) photometer
- UHC: Flame ionization detector (FID)
- Oxygen (O_2): Paramagnetic detector
- Total hydrocarbons (THC): Flame Ionization Detector (FID)

The fuel flow was measured and compared to that obtained from an exhaust species carbon balance (EPA Method 19). Natural gas usage was measured with a coriolis type flow meter.

The catalytic combustion system was thoroughly instrumented with miniature thermocouples and pressure taps. The gas temperatures at the preburner outlet, catalyst inlet, catalyst inter-stage and catalyst exit were monitored using type-N thermocouples. Static pressure taps were positioned so that the pressure drops across all three of the main components; the preburner, fuel-air premixer and catalyst bed were determined. Dynamic pressures were measured using Kistler brand pressure probes. Fuel-air ratio gas sampling used fixed rakes (sampling isokinetically) located immediately upstream of the catalyst module inlet. A near infra-red (IR) camera was mounted to view the exit face of the catalyst module through a quartz window in the burnout zone leading to the combustor scroll and turbine inlet nozzle vanes. Although the IR camera was not routinely calibrated to give accurate temperature measurements, it enabled the temperature uniformity of the catalyst module to be continuously monitored.

3.2 Engine Test Cycle

The Xonon® 2.0 combustion system was designed to operate efficiently at or near 100% load conditions. While the engine could operate at partial load, the system was optimized for fully loaded 100% speed conditions for both performance and low emissions. Although the Continuous Emission Monitoring System (CEMS) measures emissions during the entire engine cycle (from start to stop), inherent sampling delays in the analyzers make it difficult to gather meaningful transient data. All of the RAMD emissions data summarized for this report are at full engine load conditions. This strategy is in conformance to the proposed amendment to part 51 of chapter I of Title 40 of the Code of Federal Regulations as to the demonstration of pollution control technologies[1].

If a Xonon® combustion system is to be operated at varying loads (i.e., less than full load), the combustor would need to be equipped with an air by-pass valve allowing some of the combustor air to be diverted from the core combustion flow. The by-pass valve would also be necessary to meet partial load emission requirements.

IV. RAMD

RAMD (Reliability, Availability, Maintainability, Durability) is a program that is supported and recognized by a number of important third-party organizations including the California Air Resources Board, the California Energy Commission, the U.S. Department of Energy, the U.S. Environmental Protection Agency, the Electric Power Research Institute, and the Gas Technology Institute. The primary functions of the CESI RAMD effort were to:

- Define and update the requirements of the development program
- Predict reliability improvement
- Quantify demonstrated reliability
- Apportion unreliability
- Identify pathways to attain the reliability goal
- Quantify the importance of each problem
- Track problem resolution

4.1 Basic Definitions

During the course of operating the SVP unit, events (either planned or unplanned) took place that would affect the operation of the engine. Each of these events was categorized according to the ANSI /IEEE Std 762-1987 guidelines that define RAMD parameters. The following event categories/definitions were utilized during RAMD operation:

Objective of RAMD test operation

The major objective was to continuously operate at maximum capacity to quickly accumulate run hours, subject to additional inspection and test requirements, to support ongoing commercial development of the Xonon® combustion system. In support of that goal, data were gathered to reflect the reliability, availability, maintainability and durability of the Xonon® combustion system.

Deactivated Shutdown

The unit is not "active" and is not intended to be available to support the stated test objective. For purposes here, deactivated shutdown corresponds to those periods of time when the engine is not assembled in the "RAMD configuration".

Reserve Shutdown

The unit is available for operation according to the test objective, but is currently shutdown by choice. A shutdown for a customer demonstration, for example, would be considered a reserve shutdown.

In Service

The unit is operating in the configuration necessary to support the test objective.

Planned Outage

The unit is not available for operation due to a shutdown that has been defined in advance. A specific time duration for advance planning is not defined in the literature, but the intent of the activity should be consistent with the test objectives in order for it to be considered planned. Examples of planned outages would include.

- Site maintenance activities requiring a shutdown
- Inspection of the catalyst axial support structure
- Inspection of key combustor components per recommendation by a structural engineer
- Modification of the transition piece to change bypass air
- Installation of upgraded components/control system

Note that the timing is not necessarily defined in advance, but is based on the analysis of data using appropriate guidelines as determined by the team.

Basic / Extended Planned Outages

The predetermined time estimate to execute a planned outage represents the basic planned outage time. If during this planned outage, the actual work takes longer than expected, the remainder of the outage period becomes an extended planned outage. (The distinction is not important for our current purposes, and would primarily come into play when considering maintainability.)

Unplanned Outage

The unit is not available to support the test objectives due to circumstances for which down time could not be, or was not, planned in advance. Unplanned outages are further categorized as either forced or maintenance outages, depending on the urgency of need for the shutdown. The distinction comes into play if we use the forced outage rate (FOR) to characterize unit reliability.

Forced Outage

The unit is not available due to a condition beyond the control of the operator, which requires that the condition be corrected before the end of the next weekend. There are various classes defined based on specific time frames, but the distinctions are not currently important for this application. As an example, a high CO condition, which would lead to a permit violation, might force a decision to shutdown immediately.

Maintenance Outage

The unit is not available due to a condition which requires a shutdown prior to the next planned outage, but which can be deferred until after the next weekend. Note that we could choose to shutdown sooner (even immediately), but if the unit could operate satisfactorily in a way consistent with the test objectives beyond the next weekend, it is considered a planned outage.

Period Hours

This is the total time span of interest, during which the unit configuration can support the intended test objective. It consists of available and unavailable time. The remainder of the calendar time would be considered deactivated shutdown hours.

Period Hours (PH) = Service Hours (SH)
+ Reserve Shutdown Hours (RSH)
+ Planned Outage Hours (POH)
+ Forced Outage Hours (FOH)
+ Maintenance Outage Hours (MOH)

4.2 Reliability

Reliability is defined as the percent of time in the period of interest during which the unit is not in a forced outage state. The RAMD reliability goal was 98%. The ANSI /IEEE Std 762-1987 guidelines suggest the use of forced outage rate (FOR) as a measure of unreliability. Reliability is the complement to this value.

$$\text{Reliability (RF)} = 1 - \text{Forced Outage Rate (FOR)}$$

$$= \frac{\text{Period Hours (PH)} - \text{Forced Outage Hours (FOH)}}{\text{Period Hours (PH)}}$$

Substituting the expression for period hours,

SH + (RSH + POH + MOH)

Reliability (RF) = ---
SH + (RSH + POH + MOH) + FOH

Note that since FOH >= 0, any non-zero time logged as RSH, POH or MOH will result in a net increase in reliability, since the net increase relative to the numerator will be greater than the net increase relative to the denominator, resulting in a larger quotient.

4.3 Availability

The percent of time in the period of interest in which the unit could be operated to meet the test objectives

$$\text{Availability (AF)} = \frac{\text{Service Hours (SH)} + \text{Reserve Shutdown Hours (RSH)}}{\text{Period Hours (PH)}}$$

The goal of this program is to meet an availability of at least 96% before replacement is required.

4.4 Maintainability

The maintainability of the test catalytic combustor will be measured as the mean time to repair or replace (MTTR). MTTR is defined as the sum of the products of the average part failure rate and the part repair or replacement time divided by the sum of the part failure rates.

The mathematical model for calculating the MTTR is:

$$MTTR = \sum(\lambda * Rp)/\sum(\lambda)$$

Where λ = average part failures per thousand hours
Rp = repair time required to perform a corrective maintenance action in hours.

The data obtained was to be used to identify repair technologies and fault isolation techniques.

The initial maintainability design criteria (those items designed into the system) included:

1. Repairability
2. Simplicity of design
3. Availability
4. Modularity

4.5 Durability

The durability of the catalyst module and the combustion system is defined as the ability to continue to meet the performance goals after a specified extended period of time. In essence, the system must meet and go beyond all RAM requirements. For the purposes of this project, this extended time period will be defined as Mean Time Between Overhaul (MTBO) or the reduced hours defined by the availability. Durability is thus the actual time to overhaul or for replacement divided by either the defined MTBO (8,000 hours) or the reduced number of hours that defines the availability goal (7,680 hours @ 96% availability). To be considered durable the combustion system would have to exhibit a number greater than one.

If the combustion system continues to operate and meet the required performance after the 8,000 or 7,680 hours used as the measure, it will enter the durability phase of the test program. Testing will be continued until such time as the gas turbine exhaust NO_x, CO or UHC concentrations exceed certain levels. To provide some definitions of these levels the NO_x concentration used for evaluation purposes will be 3 ppmvd, the CO 10 ppmvd, and the UHC 10 ppmvd. If these levels are exceeded the catalytic combustor performance will be considered degraded to the point that it requires replacement. The hours accumulated at this point divided by the MTBO or the 7,680 hours value will be the measure of the system durability. This is sometimes expressed as one (1) subtracted from the MTBO and the result expressed as a percentage.

4.6 RAMD Calculations

A key objective of the ongoing SVP operation has been to validate the reliability, availability, maintainability, and durability of the catalyst-equipped system. The performance of the Xonon® system averaged over 8,100 operating hours is summarized in Table 4.6.1. The program exceeded the goal for reliability (goal – 98%) and fell short on availability (goal – 96%). The lower availability value is primarily due to higher than anticipated accumulation of reserve shutdown hours (RSH).

The values for maintainability and durability were not calculated due to the earlier than expected replacement of some system hardware. Maintainability is a function of the average part failure rate and repair times. Since several key components were replaced with new designs during the program due to performance limitations (most notably the axial support) or the opportunity to incorporate design improvements (catalyst foil pack), meaningful maintainability values are difficult to calculate. Similarly, the change out of several key components makes the durability calculations difficult to interpret. Accurate maintainability and durability values can be determined once the design is set and time begins to accumulate on multiple units.

RAMD Values (8128 hours)	
Reliability	99.2%
Availability	91.2%
Maintainability	NA
Durability	NA

Table 4.6.1 -- RAMD Values

V. Control System Development

5.1 Background/Objective

The objective of this task was to develop a fuel control system capable of accepting complete load loss without exceeding the turbine over-speed or surge limits. An important part of any power generation system is the ability to handle "upsets" in the distribution system and quickly come back on line. The desirable attributes are:

- Ability to follow the load requirement and to handle sudden load changes while not exceeding the turbine over-speed or under-speed limits.

- When the grid or load connection is suddenly lost, the system must be able to quickly cut back the turbine power (fuel flow) without exceeding the over-speed limits set by the gas turbine manufacturer.

- In the case of sudden load loss, it is also highly desirable for the turbine to go to a spinning idle condition, or Full Speed No Load (FSNL), rather than a complete shut down, allowing the system to come back on line quickly.

Previous testing and the development of the KHI gas turbine control system were performed in a test cell with a water brake dynamometer. This type of dynamometer load has a relatively slow response to load change inputs. For example, a step load change signal from 100% load to 0% load occurs over a period of about 2 seconds for the dynamometer compared to a nearly instantaneous loss in load for the generator open circuit situation as shown in Figure 5.1.1. Substantially faster control system performance would be required to handle load loss from a generator. The control system had been developed to handle full load steps with the available dynamometer system, but further development and testing was required to evaluate the effects of the shorter response time associated with actual on-grid operation. This work was done in this task at the SVP engine test facility.

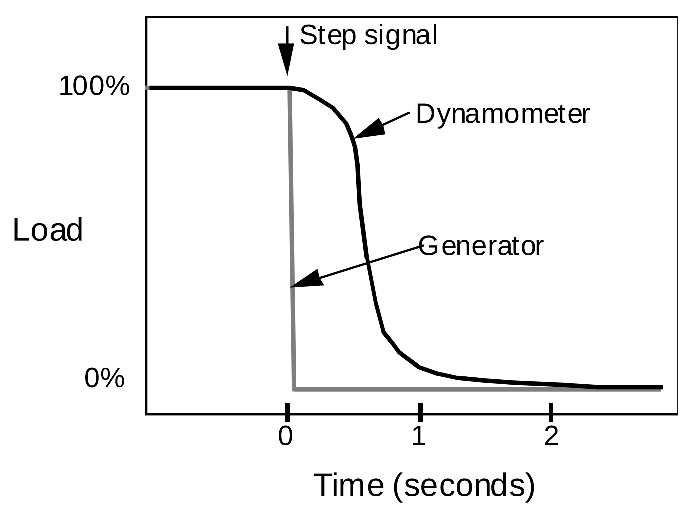


Figure 5.1.1 -- Load response comparison of a dynamometer and a generator for a step change in load set point

The fuel control for the catalytic combustion system differs significantly from conventional gas turbine combustors. There are two distinct fuel flows. Part of the fuel is used in a preburner system to heat the compressor discharge air to a temperature around 450°C (840°F). The main fuel is injected into this hot vitiated air in a specially designed mixing section. This premixer is located upstream of the catalyst module inlet. When any change in load occurs, including a sudden load loss, the total fuel flow is changed and the split of fuel between the preburner and the catalyst must be changed to maintain the catalyst within its operating window.

The current control system incorporates some elements of "feed forward", or predictive control strategies, to allow more precise control. Previous testing during the Xonon® 1 demonstration had proceeded to the point where load steps of +100% and -60% could be controlled without exceeding the gas turbine operating limits. Demonstration of a load step from 100% to 0% could not be accomplished due to the slow response of the dynamometer.

5.2 Model Based Control Strategy (Task 2.1)

It was originally believed that a model-based control strategy would be required to achieve the performance required by the power generation industry. This model based control strategy would incorporate a mathematical model of the turbine, combustor and catalyst to predict the control settings. This strategy had been applied to the control of some gas turbine systems, especially low NO_x, lean premix combustion systems. The mathematical model was then to be combined with the current control strategy to produce a fully predictive control system for the KHI engine.

5.3 Simulation Studies (Task 2.2)

As part of the development of the engine model, it would be necessary to compare the model predictions with the engine performance. Running the model against the system at the Santa Clara facility would allow one to tune the model so that it could be used as a simulator to test various control strategies and adjustments before being implemented online.

5.4 Implementation on KHI Engine Control System (Task 2.3)

After the model based control strategy had been developed, it was to be implemented on the engine and a full test program executed to further develop the system and to demonstrate the required performance. The work in this task was to include:

a. Installing the model based control algorithm in the Santa Clara KHI control system

b. Develop the system as required to permit operation of the facility.

c. Run performance tests to establish the required capability.

5.5 Program Replan

Due to unforeseen events and issues in setting up the Santa Clara facility, a "Technical and Cost Replan" was subsequently submitted to the Commission in May 1999. The following describes the deviations from the original plan as it pertains to the Fuel Controls Development.

As a supporting task to the shakedown of the facility and combustor performance mapping, substantial development of the synchronization, breaker and combustor control systems was required to provide stable and reliable operation on the power grid. In addition, control algorithms were developed to handle the operation of the combustor while maintaining low emissions levels, and some testing was conducted with rapid programmed load changes. This work suggested that the best approach to achieving an operating system with the required performance would be to utilize the existing control algorithm, with added control logic as necessary to handle large load excursions. This is in contrast to implementing a new model based control strategy.

At the time of the replan, the existing control system allowed for reliable, extended operation of the facility with low emissions and under normal operating conditions. This system provided acceptable performance during startup, shutdown, loading and unloading under controlled conditions, in addition to some load step capability as required for combustor and system testing.

In order to complete development of the control system to achieve acceptable load step control under typical commercial operating conditions, a subsequent phase of testing was planned. This testing was to commence after substantial operating time had been logged on the RAMD test, and would identify control parameters and possibly additional logic required to meet the required performance targets for load steps.

5.6 Transients Control Development and Testing

Many of the test runs overlapped each other in order to make the best use of the engine test availability. In order to present these in an organized manner, test runs have been grouped by mode of operation rather than chronologically.

5.6.1 Load Following

Load following is the ability to react to changes in system load. This can be either a response to load going on-line or off-line in an islanded system (such as in an industrial plant), or dispatched requests when connected to the grid. A characteristic of a well-controlled turbine-generator set is its ability to make large load steps without losing stability. These tests addressed a wide range of load levels and step changes in order to tune various parameters that control both stability and ramp rates.

One of the first efforts was to be sure that the system returned to a stable, steady state condition after each load step. After preliminary observations through a full range of loads, it was apparent that improvement in load stability was greatly needed. After some investigation, it was determined that there are two rate-limiting factors in the engine control logic. One factor determines the main fuel flow (Wf,main) demand based on speed droop, and the second factor is the Proportional, Integral and Derivative (PID) parameters of the main fuel valve driver. It was subsequently found that the Wf,main demand PID output was slower than that of the main fuel valve driver, and is therefore the appropriate set of parameters to tune.

The first stability tests were run on 300 kW load steps from 600 kW to 300 kW. The initial load plot is shown in Figure 5.6.1.1. After many runs from 600 kW to 300 kW while tuning all three Main Demand PID terms, this load step was much more stable as can be seen in Figure 5.6.1.2. The next objective was to speed up the load change by changing the kW ramp rate. As could be expected, this introduced some instability that had to be eliminated by simultaneously re-tuning the Main Demand PID parameters as before. The result is shown in Figure 5.6.1.3. Load steps were then increased to 600 kW for a 900 kW to 300 kW load change to verify the changes on the smaller load test will perform well for a larger step. An initial run is shown in Figure 5.6.1.4. After several tuning runs with the 600 kW load step, the improvements in speed and stability are apparent in Figure 5.6.1.5.

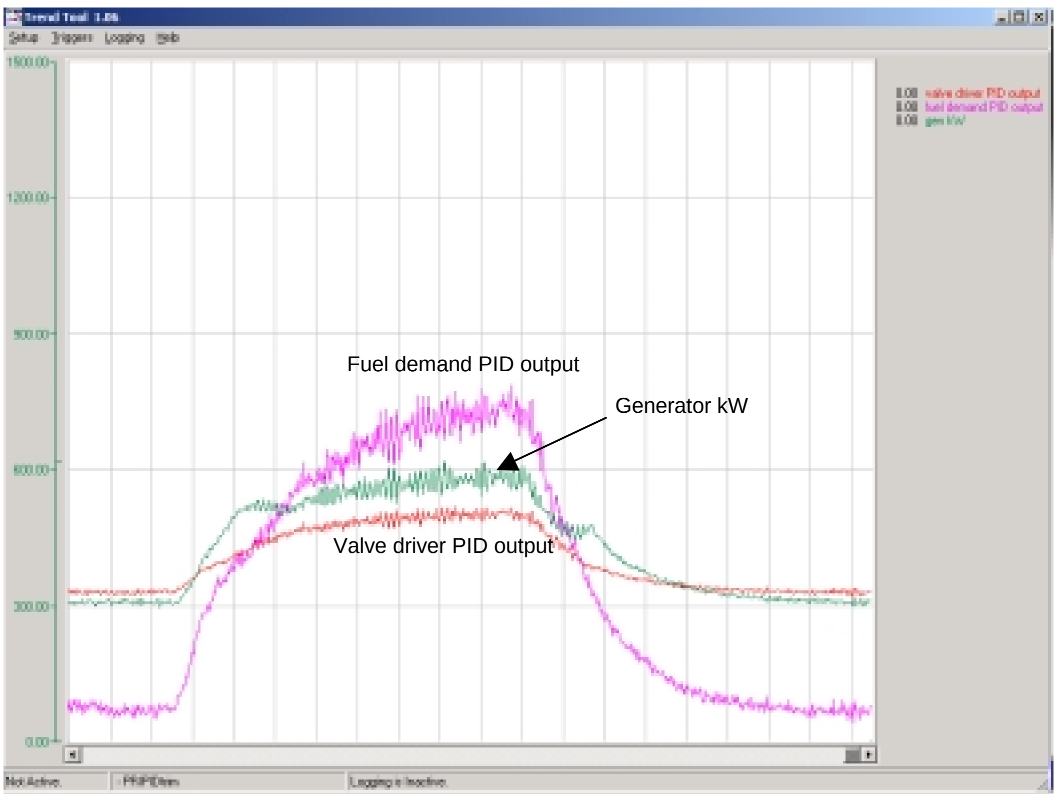


Figure 5.6.1.1 -- 600 kW to 300 kW load step prior to tuning Main Demand PID's.

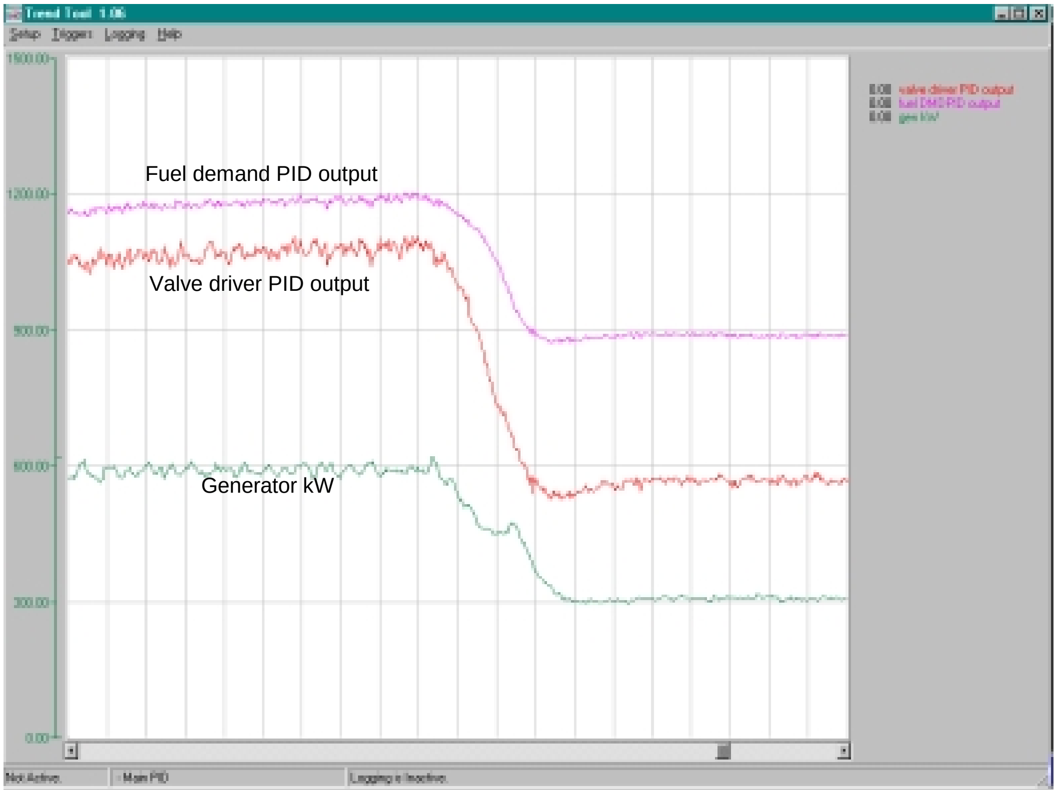


Figure 5.6.1.2 -- 300 kW load step after tuning Main Demand PID's

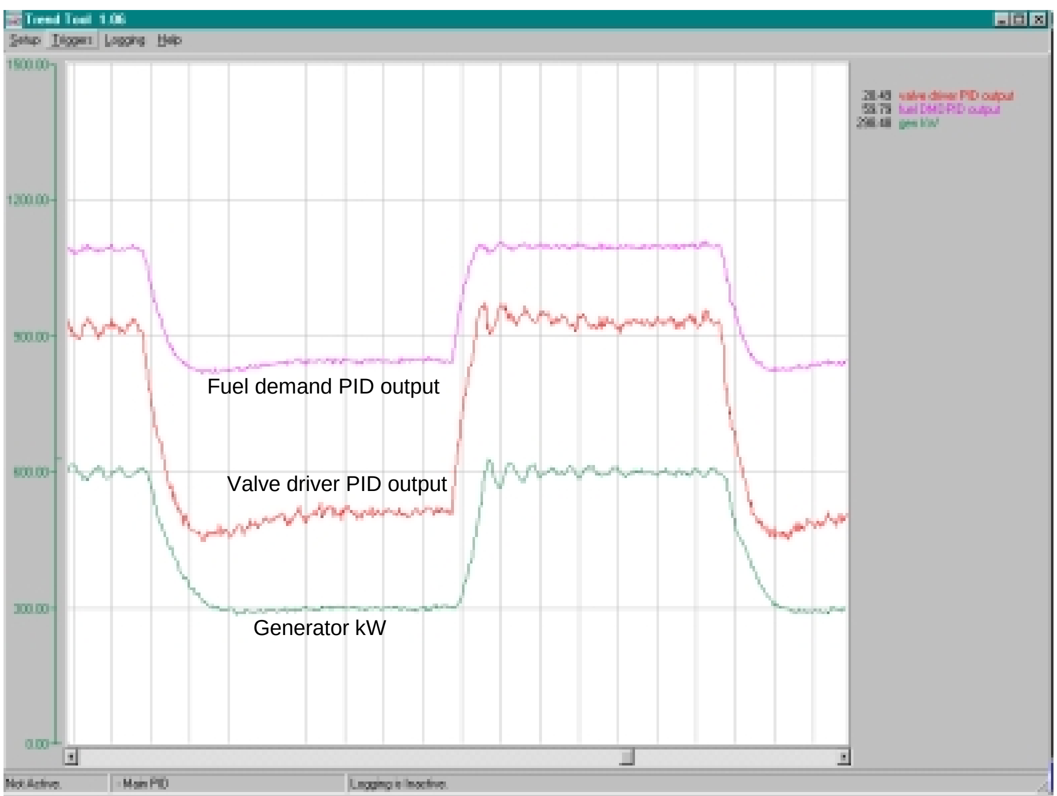


Figure 5.6.1.3 -- 300 kW load step before and after increasing the kW Ramp Rate

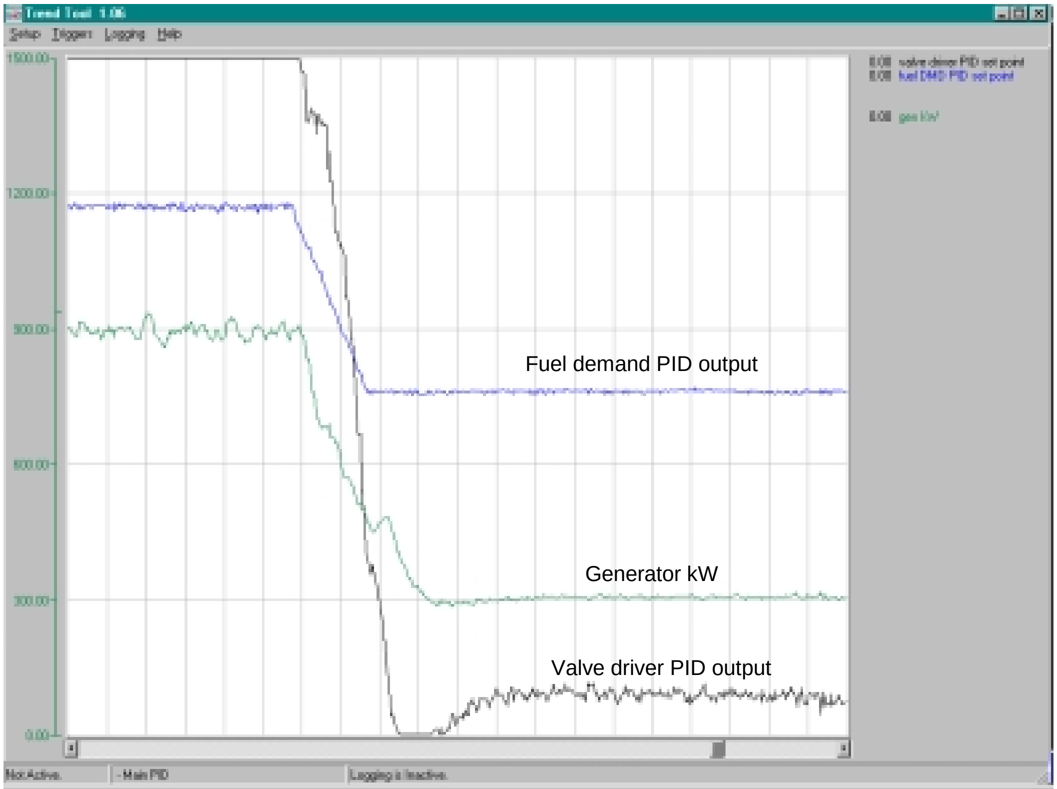


Figure 5.6.1.4 -- 600 kW load step with same parameters as tuned 300 kW load step

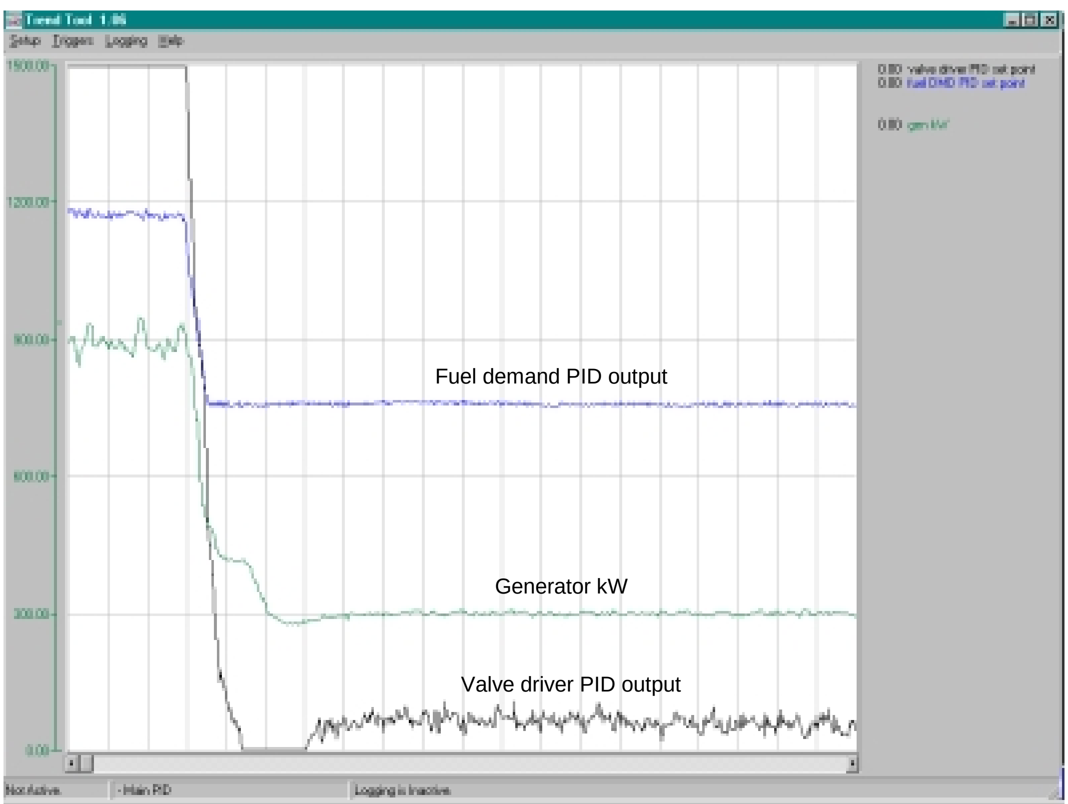


Figure 5.6.1.5 -- 600 kW load step after further tuning

The next set of load following tests was to examine intermediate load steps from 1500 kW (~full load) all the way down to 300 kW. The machine was first ramped up to 1500 kW, and then reduced to 1200 kW, 1000 kW, 800 kW, 600 kW and finally 300 kW. At 1200 kW through to 600 kW, it was very noisy and the oscillations would not stabilize. Once down to 300 kW, the load plot was significantly more stable.

One interesting phenomenon to note is that as load is increased the instabilities are not as apparent as they are on downward ramps. One possible explanation for this is the existence of acceleration torque during loading, which is not present during unloading. This is an issue that should be explored; however, it was not done during this phase of testing since we were able to dampen these oscillations by tuning the various parameters as discussed below.

Testing resumed with a load change from 1500 kW to 600 kW, as shown in Figure 5.6.1.6. An overshoot to ~533 kW occurred with the activation of the preburner's primary stabilizing logic. After on-line tuning of the PID parameters it was possible to reduce the swings to about +/- 50 kW.

Figure 5.6.1.6 -- 1500 kW to 600 kW load step

After some investigation, we concluded that the following chain of events were the cause of the instabilities. When the load is reduced, the secondary fuel begins to increase, resulting in higher secondary zone efficiency. This initiates a load oscillation (rather than a smooth curve). The sudden change in secondary zone combustion efficiency also activated the primary zone stabilization module, reducing the oscillations. However, when this primary zone stabilization ends, the performance becomes very unstable again. The load is already unstable before the secondary zone efficiency jumps from low to high, further aggravating the problem. The primary stabilization module causes the catalyst inlet temperature to rise (i.e., by increasing the primary fuel, the fuel fed into the secondary burns more efficiently). A stable point is reached quickly, but this stability is lost as the primary fuel flow is reduced after the primary stabilization sequence ends.

As a solution, the preburner operating curve was changed to increase the preburner outlet temperature (which is controlled by the secondary fuel flow) at the point where the stability is lost. This seemed to substantially lower the amplitude of the oscillations.

5.6.2 Load Rejection

Load rejections occur when the generator breaker opens and the load drops instantaneously, resulting in the engine being in a Full Speed No Load (FSNL) state. Issues that arise are primarily associated with engine over-speed and under-speed conditions which occur when the fuel control system must suddenly adjust to a no load condition.

As in the previous tests, smaller steps were taken first to minimize potential damage to the machine. The initial load rejections were from 300 kW. In the first test, using the new PID parameters from the load following tests, the system went into uncontrollable oscillations when the breaker was opened at 300 kW. The proposed solution was to create two separate sets of PID parameters; one set would control while the breaker was open and the other set would control while the breaker was closed.

The first load rejection with the new dual PID parameters logic in place was from 300 kW. This resulted in numerous oscillations in speed, which eventually smoothed out after about 40 seconds, as shown in Figure 5.6.2.1. Figure 5.6.2.2 shows the effect of tuning the PID parameters after additional load rejections from 300 kW. Figure 5.6.2.3 shows a 600 kW load rejection with the same PID parameters as above. Additional tuning of the PID parameters was performed to minimize the over-speed/under-speed excursion and the time to stabilize the turbine at FSNL. The key target was to ensure turbine speed would not exceed the OEM recommended 108% speed. Load rejections were performed from 300 kW, 600 kW, 900 kW, and 1050 kW load levels, and are shown in the Figures 5.6.2.4 and 5.6.2.5.

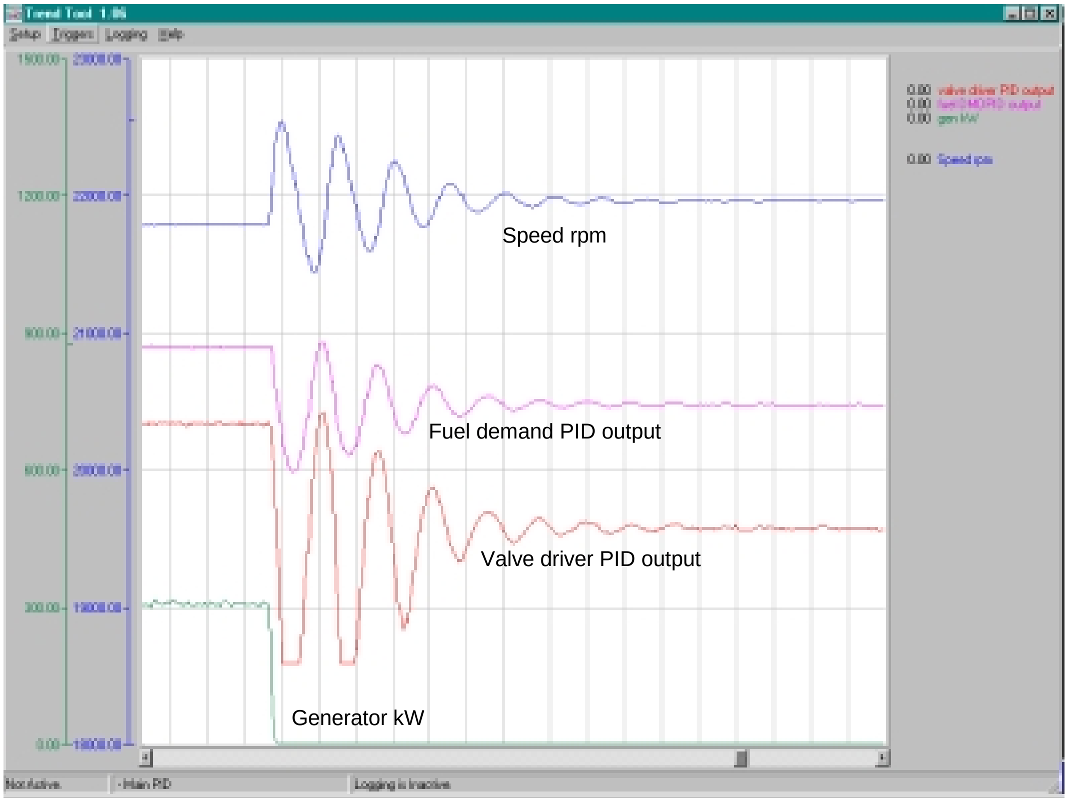


Figure 5.6.2.1 -- 300 kW load rejection prior to tuning

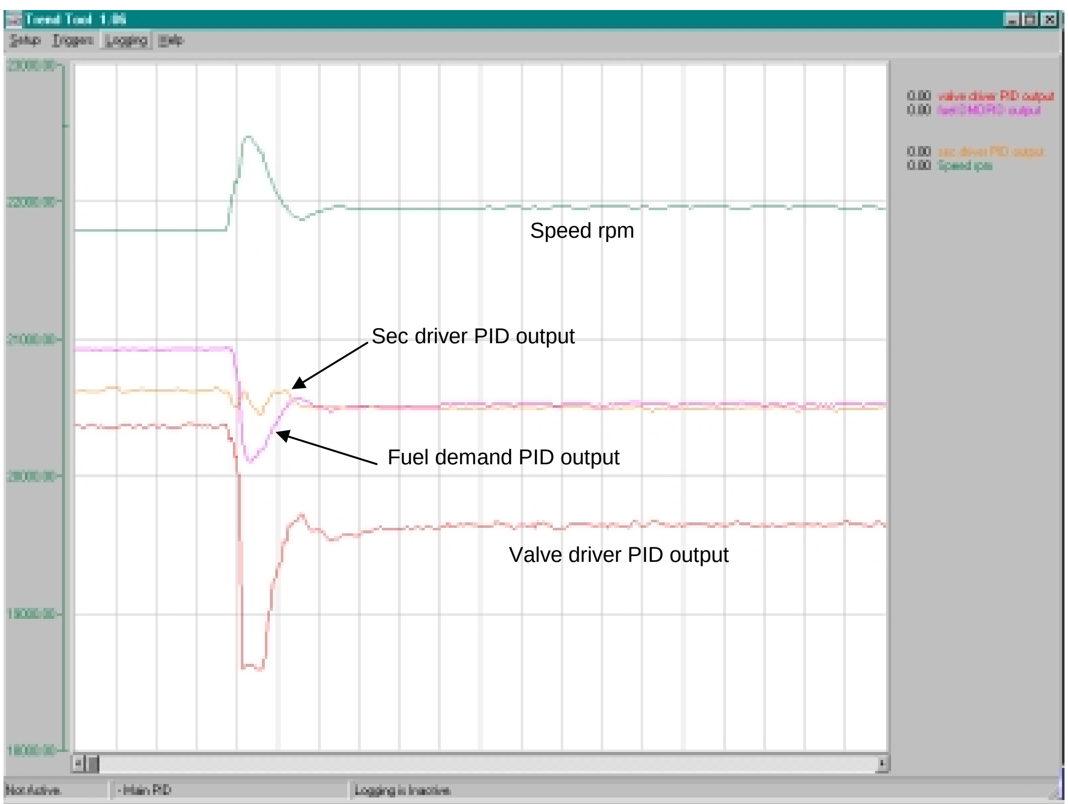


Figure 5.6.2.2 -- 300 kW load rejection after tuning

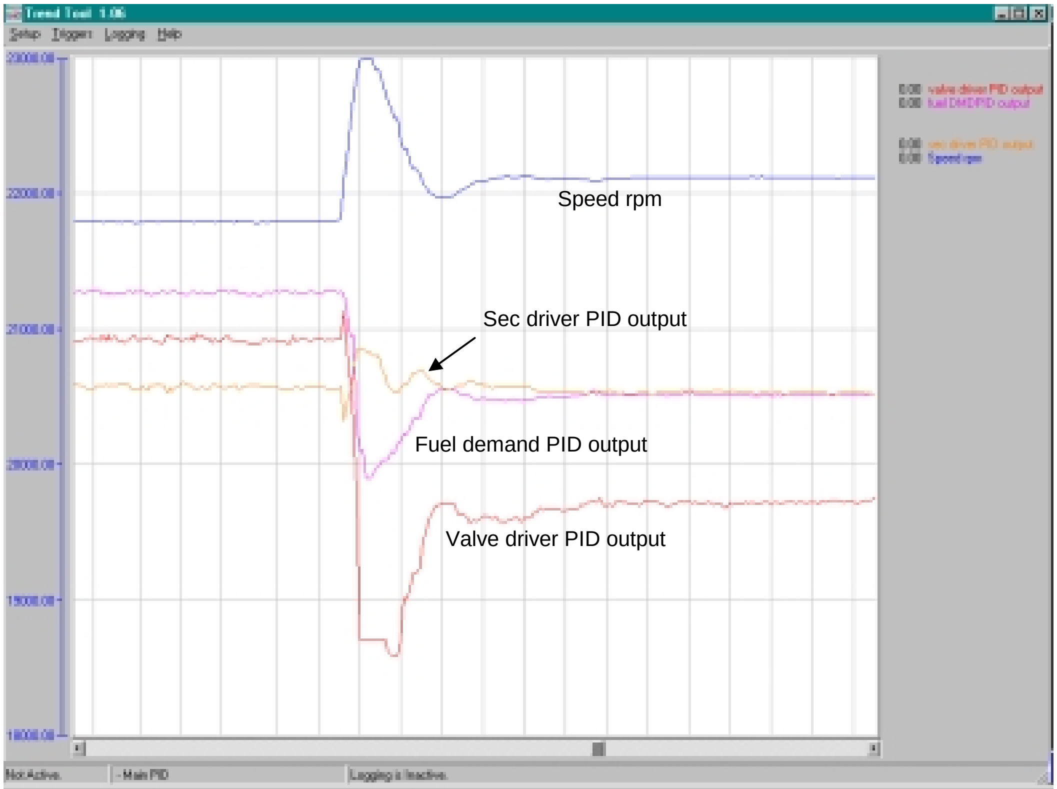


Figure 5.6.2.3 – 600 kW load rejection with same PID parameters as the 300 kW load rejection

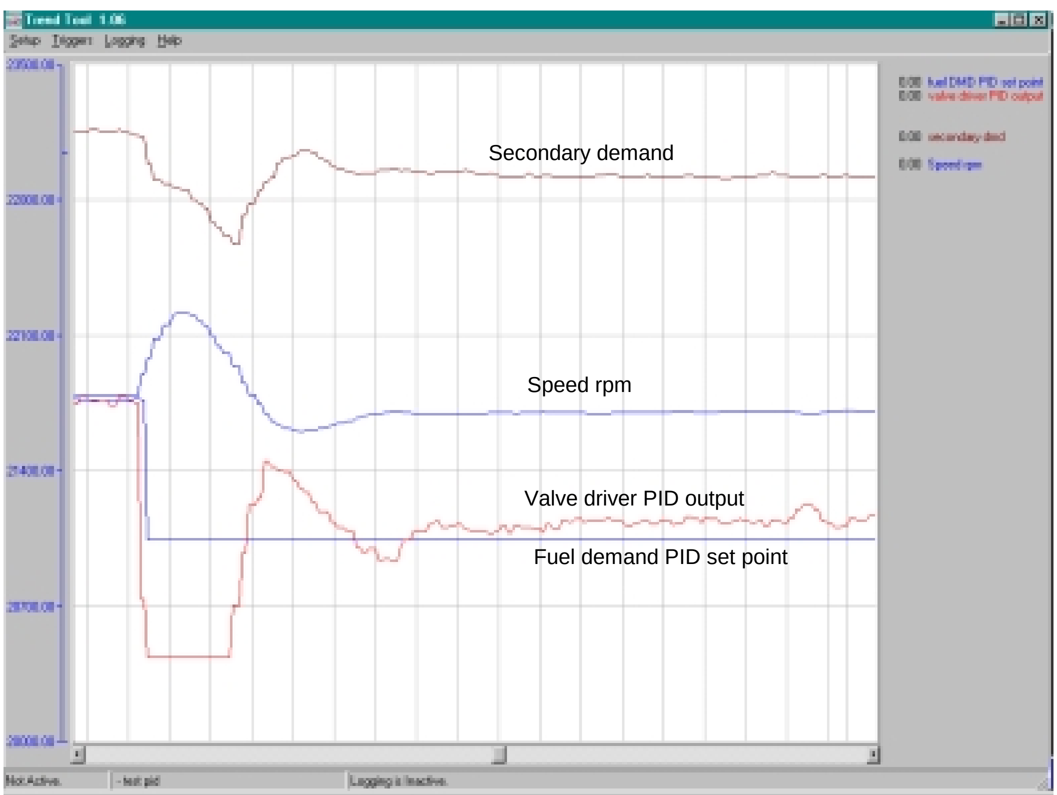


Figure 5.6.2.4 -- 300 kW load rejection (1.9% overspeed, -0.9% underspeed)

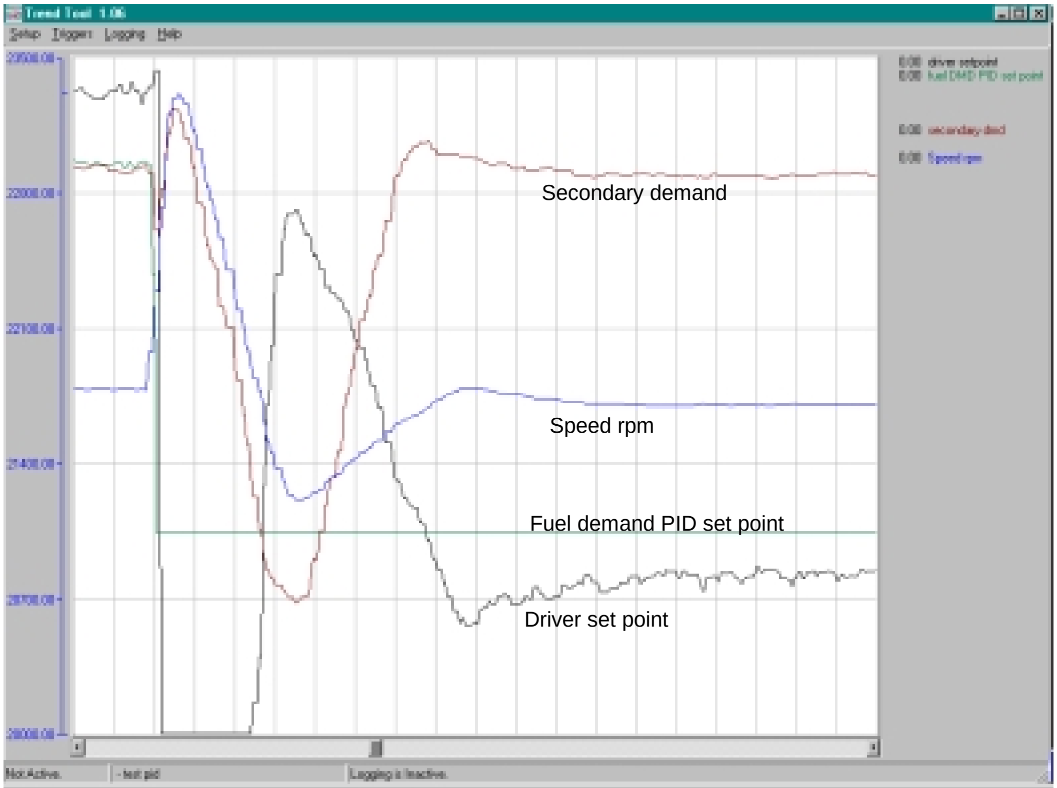


Figure 5.6.2.5 -- 1050 kW load rejection (6.9% overspeed, -2.7% underspeed)

5.6.3 Breaker Auto-Resynchronization

Following a load rejection, it is desirable for the machine to automatically resynchronize with the grid. In order for a generator to synchronize with the grid the rotational frequency of the shaft must match the frequency of the grid within +/- 0.5 Hz. With an engine speed of 21800 rpm, this corresponds to +/- 181.67 rpm in engine speed. The system dynamics during an unload result in a time lag before the engine speed settles to steady state. These speed oscillations must fall within the specified rpm range for successful grid resynchronization to occur. Since a resynchronization won't occur until a by-pass relay has timed out, the timeout delay can be used to allow sufficient time for the engine speed to stabilize.

Several load rejections were performed to determine the time it takes for stabilization. Figure 5.6.3.1 shows one of these test runs. It was determined that the timeout delay needs to be at least 15 seconds before the generator frequency stabilizes to within +/- 0.5 Hz of the grid frequency.

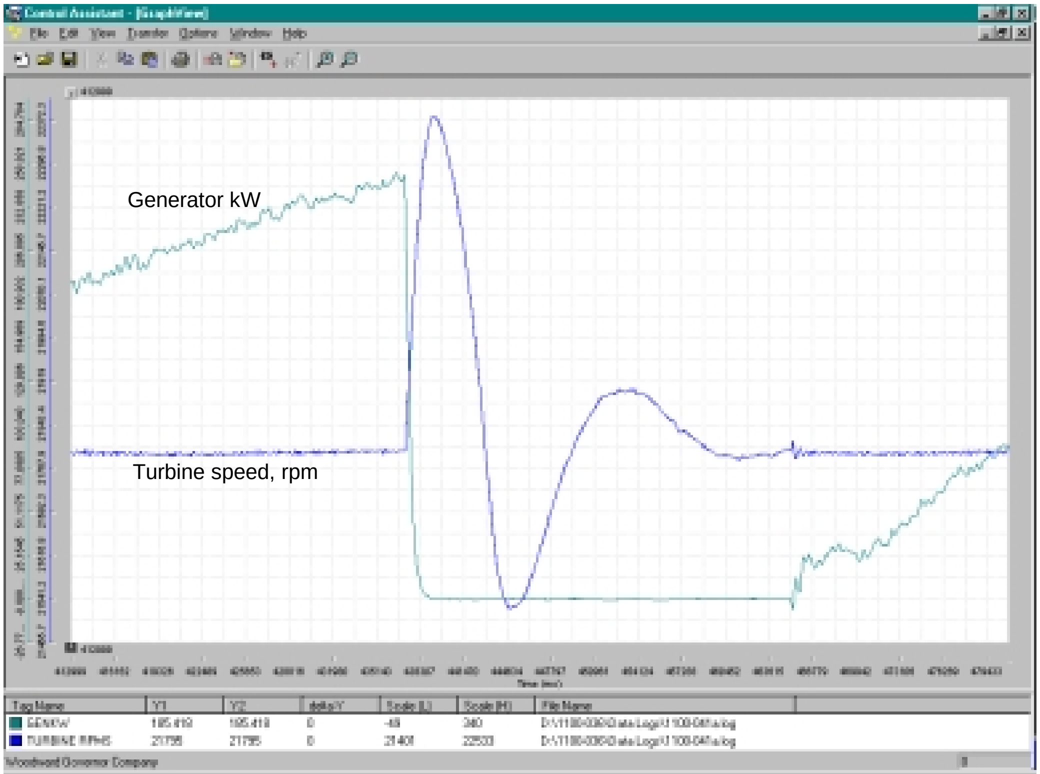


Figure 5.6.3.1 -- Engine speed oscillations after load rejection and before breaker re-synchronization

5.7 Controls Development Conclusions

The primary objective of this task was to further develop a fuel control system capable of handling "upsets" in the distribution system while not exceeding the over-speed limits specified by the engine manufacturer. The original plan was to develop a model based fuel control system. However, as described in the Replan, the existing control system was sufficient to use as a starting platform from which a robust control system could be developed through testing and tuning. Specific accomplishments include:

- Instabilities that occurred during 300 kW and 600 kW load steps were successfully eliminated by tuning the Main Demand PID parameters
- Part load instabilities were eliminated by modifying the operating curve to increase the preburner outlet temperature, avoiding a region where the primary stabilization module cycles on and off.
- Main Demand PID parameters were tuned to prevent exceeding over-speed limits when rejecting load from 300 kW, 600 kW, 900 kW, and 1050 kW.
- After a load rejection, the timeout delay before automatically re-synchronizing to the grid was adjusted such that there was sufficient time for the generator frequency to fall within +/- 0.5 Hz of the grid frequency.

VI. RAMD Test Results

The RAMD test program accumulated 8,128 hours of on-grid power generation over the course of two years. The intent was to accumulate operating hours as quickly as possible with minimal interruption due to planned or unplanned shutdowns. The RAMD tests were periodically interrupted to perform development tests on sub-systems including the combustion control system, automated bypass integration, premixer and the catalyst container components. Other non-combustion system test interruptions include those related to test cell and computer/communication upgrades.

The RAMD hours were primarily accumulated on four (4) combustor builds. The testing occurred in three phases with new or reworked components/systems implemented during each phase. Table 6.1 shows the phase, engine build and hour accumulation for the entire RAMD test program. Discontinuity in the numbering of the combustor builds is due to the intervening development tests mentioned in the previous paragraph.

	Build	RAMD Hours	Build Hours
Phase I	KHI-2 build 3	0 – 2,064	2,064
	KHI-2 build 3A	2,065 – 4,128	2,064
Phase II	KHI-2 build 5	4,129 – 7,356	3,228
Phase III	KHI-2.1 build 1F	7,357 – 8,128	772
Total RAMD Hours			**8,128**

Table 6.1 -- RAMD engine builds and operating hours

The turbine system is fully instrumented to collect performance parameters for monitoring and control. A separate continuous emissions monitoring system (CEMS) measures pollutant emissions in the engine exhaust stack, and provides this information to the main control system. Data for all parameters are recorded and stored at one-second intervals. Data reporting to demonstrate regulatory compliance is handled independently.
Sections 6.2 – 6.4 present the emissions performance data from normal operation of the CESI turbine at Silicon Valley Power BAAQMD Plant no. 11840, Permit no. 18547, Source no. S-1.

In addition to the performance data, some of the data records are tagged with a code, indicating the occurrence of an "event" during the period in which that record was being collected. Depending on the nature of these events, some of these records have been identified as inappropriate for inclusion into the emissions results. These records are then highlighted and tagged with the appropriate event code and stored in the data collection system. (see Appendix E for a description of the event codes)

For purposes of this data presentation, an "event" is defined as any occurrence outside of normal controlled operation that might impact the operation or performance of the turbine facility. Specifically, when the indicated exhaust emissions do not accurately represent the actual emissions produced by the facility, or when operating conditions are not representative of typical "normal" steady-state operation at the maximum design load, these periods are classified as “events.” Examples of events not included in the emission averages would be system calibration, engine start up and shutdown. “Events” as they relate to emission data collection may or may not coincide with “events” used to calculate reliability.

An Event Criteria data sheet was used to categorize all of the observed events by keyword, and describes each event in sufficient detail to explain the treatment of data collected during the period of the event. The Event Log lists each observed event during the entire period of the data collection, including any additional comments to further explain the particular event. Specific occurrences of the events are indicated by keyword in the Data Table along with the parameter. Table E-1 in Appendix E shows the codes.

A detailed test log was kept to track engine operating conditions and to record any testing anomalies. If an operating event occurred, the cognizant test engineer would evaluate the event and determine the appropriate course of action. If the event occurred when the testing was unmanned, the test cell control logic would evaluate the event and contact a test engineer through an automated paging system. If the event were deemed severe, the test cell control logic would automatically shut down the engine.

6.1 Emissions Measurements

The exhaust emissions were monitored with an ML661 extractive CEMS specifically designed for industrial applications incorporating proven analyzers that provide exceptional stability and accuracy. The data acquisition system (DAS) records data and generates reports. The basic function of the ML661 extractive CEMS is to provide emissions data that can be used for process control and/or for compliance with local, state and federal regulations. At a minimum, the ML661 satisfies the requirements of the US EPA 40 CFR .

The ML661 system is designed for 24-hour continuous automatic operation. There are several different modes of operation, all controlled by a General Electric GE 90-30 Programmable Logic Controller (PLC) mounted inside the CEMS rack. Except during calibration mode, which occurs every 24 hours, the system is in the sample mode of operation, with sample gas routed to all analyzers. During each 24-hour period, approximately 23 hours and 45 minutes are available for sampling and 15 minutes are dedicated to an automatic calibration check.

6.1.2 Data Acquisition System

The DR9075 data acquisition and handling system (DAS) consists of a Pentium microprocessor system with a 1GB hard drive for data storage, a 1.44 MB floppy drive and 32 MB of random access memory. Auxiliary components include a printer, serial mouse, 9600 baud modem, and Monitor Labs’ Graphical Operator interface program.

The DAS operates under a UNIX operating system platform running Monitor Labs’ proprietary software. This software collects monitored data through serial data communications with the GE 90-30 PLC. The DAS receives the time-based data averages from the PLC for each parameter measured, which can be configured to accumulate for intervals from 1 to 15 minutes. The DAS stores this data, performs final data reduction (calculates emission parameters such as lb/hr), and formats this data into reports required by local, state and federal agencies.

6.1.3 Measurement Equipment

The following emissions measuring equipment was used for the RAMD test program:

- CO: ML 9832 Nondispersive Infrared Absorption Analyzer
- CO_2: ML 472 (Servomex 1415) Nondispersive Infrared Photometer
- NO_x: ML 9841AS Gas-Phase Chemiluminescence Spectroscopy Analyzer
- Dry O_2: ML 422 (Sevomex 1420) Paramagnetic Analyzer
- THC: Rosemount 400A Flame Ionization Detector

Detailed specifications for each analyzer or detector are shown in Tables A1 – A5 in Appendix A.

6.2 Phase I Testing

6.2.1 Phase I Combustor Configuration

The purpose of this build was to replace the existing KHI-2 catalyst with the new Xonon® 2.0 RAMD catalyst. The Phase I testing occurred over the course of two combustor builds (denoted 3 and 3A). This combustor was built to the KHI-2 Xonon® 2.0 configuration (see Figure 6.2.1.1) with some minor modifications as listed below:

Build 3 hardware modifications (0-2065 RAMD hours)

- Reduced catalyst instrumentation
  - 8 inlet gas thermocouples
  - 4 interstage gas thermocouples
  - 8 outlet gas thermocouples
  - 8 fuel/air sample tubes
- Swirler was glass beaded to remove thermal paint from earlier tests
- An external main fuel manifold was designed and installed
- New C-rings in the outer case and inner dome
- TBC removed from primary fuel injectors
- Modification of pigtail pilot
- Modification of pilot manifold supply tube
- Modification of swirler vane assembly

Build 3A hardware modifications (2066-4128 RAMD hours)

- Thicker finger seals (0.005 inch) installed in the outlet stage guide ring
- 1 inch honeycomb spacer between interstage axial support structure and outlet stage catalyst
- Installation of a new secondary fuel muff
- Installation of 27 type N thermocouples on BOZ liner to measure BOZ flame front location

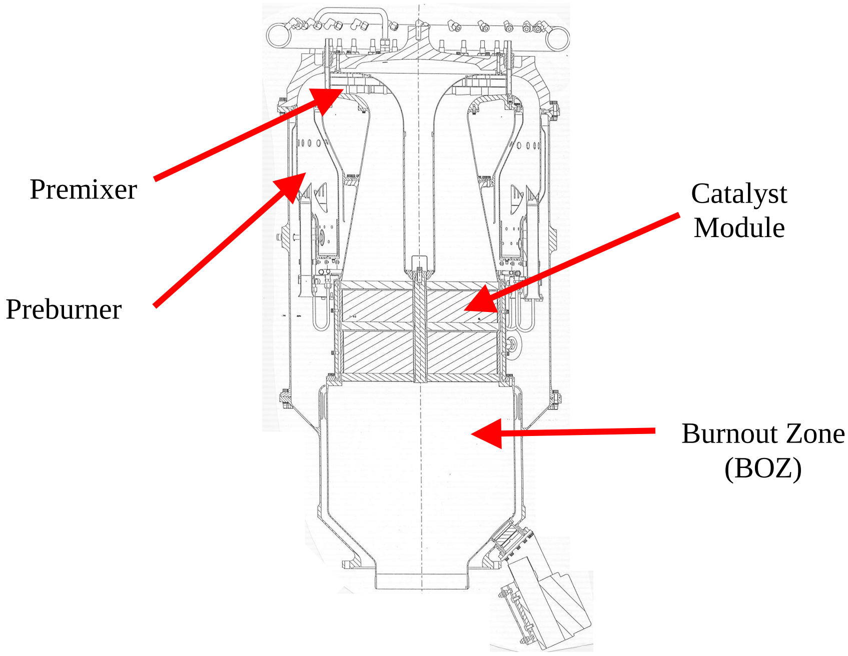


Figure 6.2.1.1 – KHI-2 Xonon® 2.0 Combustion System

6.2.2 Phase I Emissions Results

The emission levels were measured and recorded at one-second intervals. Table 6.2.2.1 shows a summary of the averaged emission results for NO_x, CO and UHC. The raw one-second interval data were averaged over the course of 30-minute blocks of time. In addition, data were summarized in one hour and three hour rolling averages. All emission data are corrected to 15% oxygen. The table shows that the average emission level for each constituent is quite low and within the respective program goals.

Figure 6.2.2.1 is a graph showing the 30-minute averaged NO_x data versus testing date. The data clearly show that the NO_x level never exceeded the 3.0 ppm goal. Figure 6.2.2.1 also shows that the NO_x levels began to increase during the colder months. In early operation (June through September), the load and ambient temperature were both high, and NO_x performance was uniformly very good. In October, the ambient temperature began to drop, and by the end of the month, NO_x levels were periodically reaching levels over 2 ppm, and CO emissions were also exceeding normal operation levels.

After some investigation, it was determined that the probable cause of the high CO was due to a capacity limitation of the gearbox. As ambient temperature drops, the power generation capacity of the turbine increases, but the gearbox capacity does not change. So at the lower ambient temperatures, the turbine and combustor systems operate at part load conditions. Since the combustion system was not optimized for the widest turndown range, high CO emissions resulted.

The higher NO_x emissions can also be attributed to the gearbox capacity limitation, which effectively operates the engine and combustor at part load conditions. Under part load conditions, the preburner outlet temperature is higher than at base load conditions. Since the primary source of NO_x is from the preburner, the higher outlet temperature of the preburner resulted in higher NO_x emissions.

In addition, a portion of the higher NO_x can be attributed to the performance requirements at low ambient temperatures. In order for the preburner to maintain a constant outlet temperature, the temperature rise across the preburner must be higher for the lower ambient temperatures. The higher temperature rise results in higher NO_x emissions from the preburner.

A possible solution to the partial load operation limitation is the incorporation of a combustor bypass valve. During partial load conditions, the combustor bypass valve is opened and combustor airflow is reduced. The fuel/air ratio within the catalyst increases, resulting in improved BOZ efficiency and lower emissions. This theory was tested on October 27th 2000 when the unit was shut down to exchange the original transition piece between the engine and combustor with another that had a larger liner effective area. The effect of this change was the same as partially opening a bypass valve. NO_x emissions dropped over 1 ppm and the CO dropped over 4 ppm at the same ambient temperature. Based on these results, CESI incorporated a bypass valve system in the Xonon® 2.1 combustor configuration.

Figure B1 in Appendix B shows the 30-minute averaged data for CO. The CO data shows non-conformance to the program goal of <5.0 ppm in a relatively large percentage of the data points. In addition, the CO levels exceed the permit allowances of <10.0 ppm on two separate occasions. The preburner/catalyst fuel split and the BOZ residence time primarily determine the level of CO emissions. Development work on the preburner/catalyst fuel split issue, which is determined by the control system logic, continued during subsequent RAMD testing phases. Work on lengthening the BOZ residence time, which requires hardware changes, is currently being pursued under a company-funded effort.

Figure B2 shows the 30-minute averaged data for UHC. The figure shows that the UHC levels exceed the 5 ppm goal on a handful of occasions and never exceed the 10 ppm permit levels.

	30 minute averages (ppm)			**1 hour rolling averages (ppm)**			**3 hour rolling averages (ppm)**		
	Min	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**
NO_x	0.5	1.3	2.9	0.5	1.3	2.9	0.5	1.3	2.8
CO	0.0	1.2	12.5	0.0	1.2	12.5	0.1	1.2	9.6
UHC	0.0	1.0	9.1	0.0	1.0	9.0	0.0	1.0	8.8

Table 6.2.2.1 – Phase I emissions results

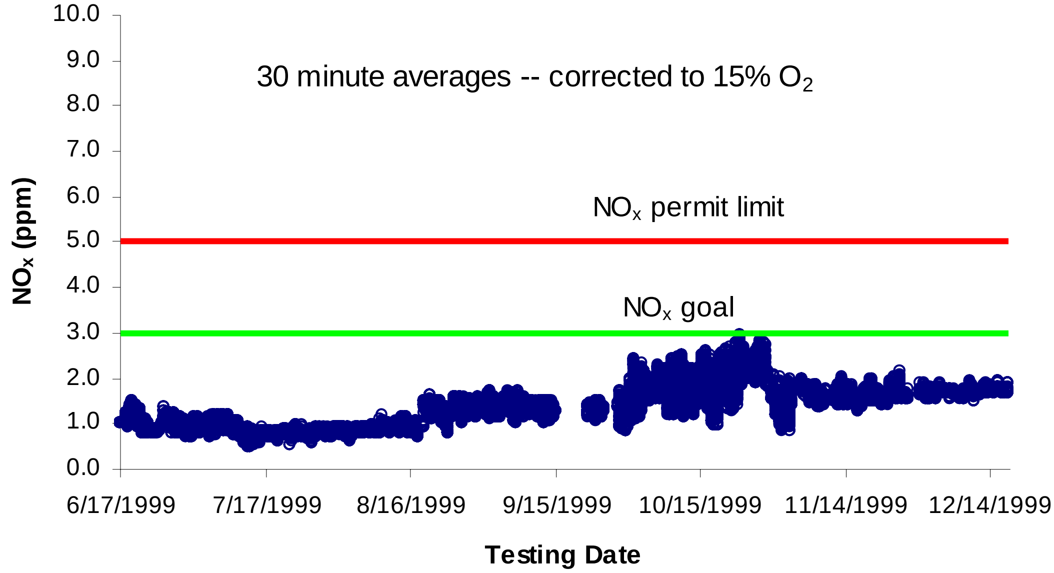


Figure 6.2.2.1 – Phase I NO_x emission results (30 minute averages)

6.2.3 Phase I Hardware Condition

<u>Build 3 findings</u>

The combustor was removed from the engine after completion of 2064 RAMD hours. The combustor was disassembled and visually inspected by Catalytica engineering personnel. The catalyst module is shown in Figure C1 in Appendix C. The result of the visual inspection is detailed below.

- The BOZ was in good condition with some minor thermal barrier coat (TBC) cracking, but no evidence of TBC spalling
- The primary tube/OD heat shield weld exhibited some minor cracking
- Fuel pegs were in good condition
- Finger seals exhibited some deformation (see Figure C3)
- No cracks found at inlet or outlet axial support structure (see Figure C4)
- Swirler vane pack was in good condition (Figure C5)
- There was a notable amount of TBC spalling off of the ID heat shield presumably caused by hot spots generated by the primary burners impinging onto the shield (Figure C6)
- There was no evidence of TBC spalling off of the OD heat shield
- The catalyst foil was in good condition

<u>Build 3A findings</u>

The combustor was removed from the engine after completion of an additional 2064 RAMD hours (total RAMD hours 4128). The result of the visual inspection is detailed below.

- The BOZ was generally in good condition (Figure C7) with some minor TBC spalling probably due to contact with the axial support structure outer ring (Figure C8)
- The outlet axial support structure exhibited cell deformation and cell wall cracking (Figure C9)
- The inner combustor liner (Figure C10) was cracked near the bolt flange (Figure C11)
- The primary tube/OD heat shield weld exhibited some minor cracking (Figure C12)
- Swirler vane pack was in good condition
- There was no evidence of TBC spalling off of the OD heat shield
- The catalyst foil was in good condition

6.3 Phase II Testing

6.3.1 Phase II Combustor Configuration

The primary purpose of this build was to integrate design improvements and hardware changes based on Phase I test results. The major hardware changes are shown in Figure 6.3.1.1 below and include the following:

<u>Build 5 hardware modifications (4129-7357 RAMD hours)</u>

- Installed an improved catalyst module design
- Replaced outlet axial support structure (Bonded Metallic Monolith – BMM)
- Transition duct holes were blocked with metal foil

The key change for build 5 was the new generation 2.0 catalyst module with improved aging characteristics.

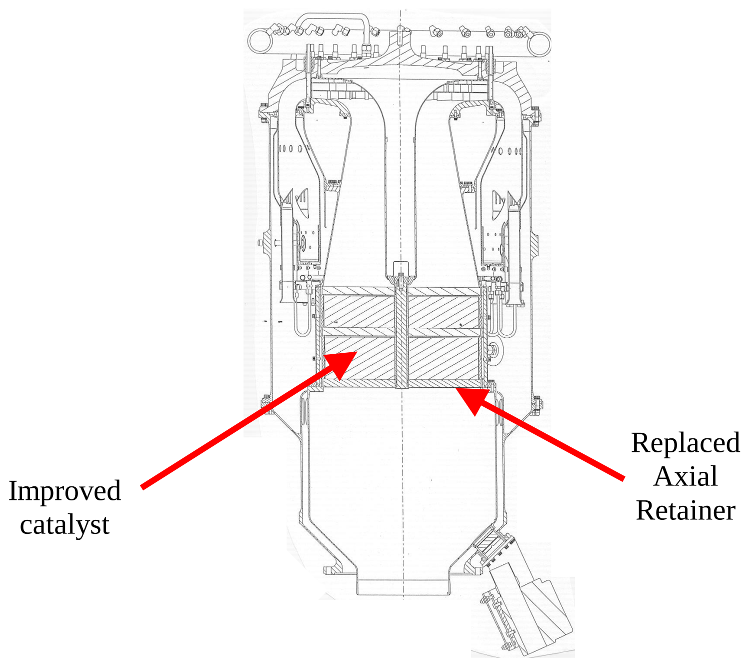


Figure 6.3.1.1 -- Build 5 KHI-2 Xonon® 2.0 test configuration

6.3.2 Phase II Emissions Results

Table 6.3.2.1 shows a summary of the emissions results for NO_x, CO and UHC. The averaged data show that all emission levels are quite low and well within the program targets. In fact, the average emission levels are modestly lower than those measured during the Phase I testing. Figure 6.3.2.1 is a graph showing the 30-minute averaged NO_x data versus testing date. The data shows that the overall NO_x levels are lower than those seen during the Phase I testing and the level never exceeds the 3.0 ppm goal.

Figure B3 in Appendix B shows the 30-minute averaged data for CO. The CO data shows fewer non-conformance points (>5.0 ppm) when compared to those seen in the Phase I testing. However, the data also shows three days where very large excursions (>30 ppm) were observed. In each case, these short-term excursions were due to modifications being made to the control system logic that determined the preburner/catalyst fuel split.

Figure B4 shows the 30-minute averaged data for UHC. Only one data point exceeds the 5 ppm emission goal.

	30 minute averages (ppm)			1 hour rolling averagee (ppm)			3 hour rolling averages (ppm)		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
NO_x	0.8	1.2	1.9	0.8	1.2	1.8	0.8	1.2	1.7
CO	0.0	0.5	94.5	0.0	0.5	73.4	0.0	0.5	25.9
UHC	0.0	0.6	7.6	0.0	0.6	5.2	0.0	0.6	3.5

Table 6.3.2.1 -- Phase II emissions results

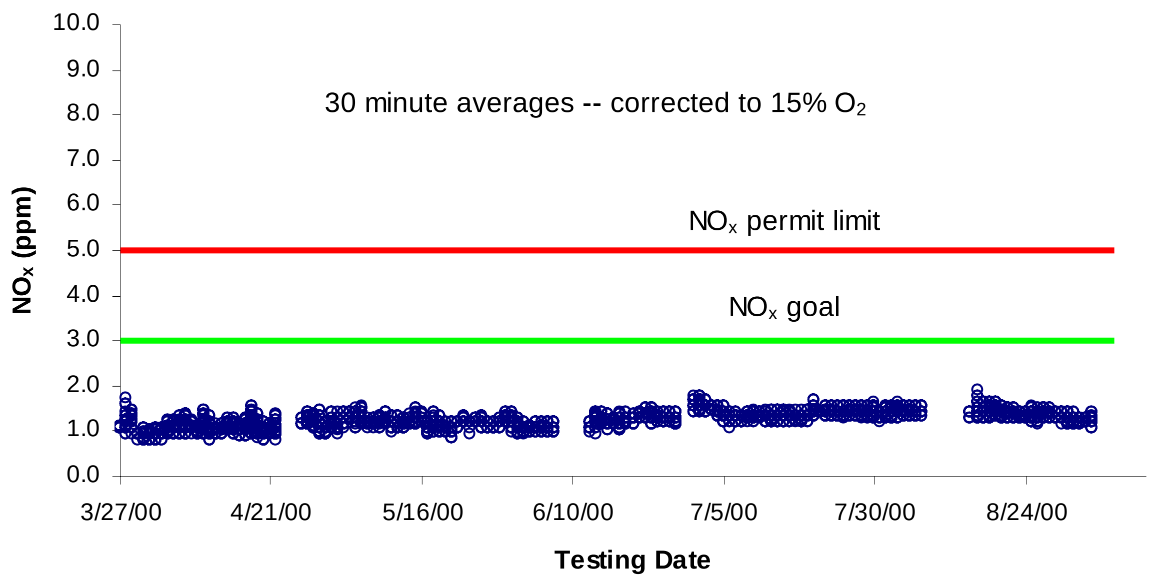


Figure 6.3.2.1 – Phase II NO_X emission results (30 minute averages)

6.3.3 Phase II Hardware Condition

The combustor was removed from the engine after completion of an additional 3,228 RAMD hours (total RAMD hours 7,357). The result of the visual inspection is detailed below.

- The BOZ was generally in good condition with some minor TBC spalling as seen from the previous build 3A test
- The inner combustor liner was cracked near bolt flange. The primary tube/OD heat shield weld exhibited some minor cracking
- Swirler vane pack was in good condition
- There was no evidence of TBC spalling off of the OD heat shield
- The stage 1 and stage 2 catalyst foils were in good condition

6.4 Phase III Testing

6.4.1 Phase III Combustor Configuration

The primary purpose of this build was to install the combustor air by-pass system and to integrate improvements in the preburner and catalyst module container. The major hardware changes are shown in Figure 6.4.1.1 below and include the following:

Build 1F hardware modifications (7358-8128 RAMD hours)

- Installed an improved catalyst container (no change in previous Phase II catalyst foil)
- Modified the existing preburner
- Installed combustor by-pass system

These changes were implemented in order to improve operational characteristics of the system, improve the life of the catalyst container and to ease assembly/replacement of the catalyst module. Operationally, the by-pass system increases the part load capability, and the modifications to the preburner improve the part load stability.

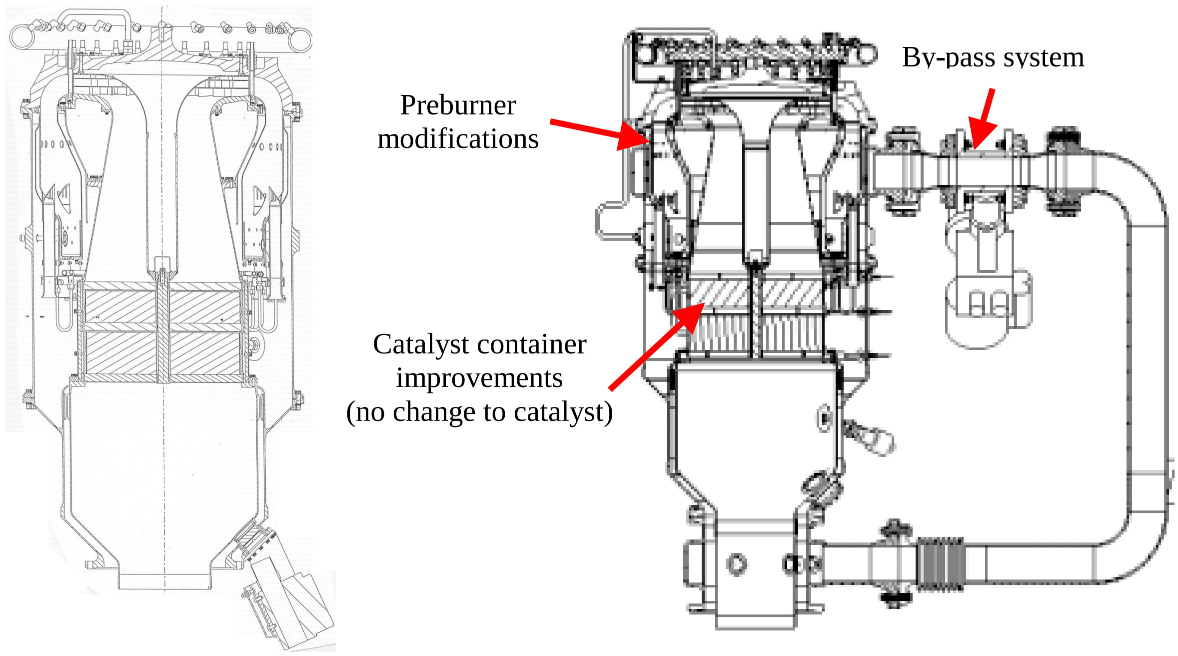


Figure 6.4.1.1 -- Xonon® 2.0 and Xonon® 2.1 comparison

6.4.2 Phase III Emissions Results

Table 6.4.2.1 shows a summary of the emissions results for NO_x, CO and UHC. As in the case of the Phase I and Phase II results, the averaged data show that all emission levels are quite low and well within the program targets. In fact, the average emission levels are lower than those measured during either the Phase I or Phase II testing. Figure 6.4.2.1 is a graph showing the 30-minute averaged NO_x data versus testing date. The data show that the overall NO_x levels are comparable to those seen during the Phase I testing, and the level never exceeds the 3.0 ppm goal.

Figure B5 in Appendix B shows the 30-minute averaged data for CO. The CO data show fewer non-conformance points (>5.0 ppm) when compared to those seen in the Phase I or Phase II testing. The figure shows that the CO levels exceed the target and permit values on one testing day. As discussed in section 6.2.2, this short-term excursion was due to modif-ications made to the control system logic controlling the preburner/catalyst fuel split.

Figure B6 shows the 30-minute averaged data for UHC. The UHC emissions are lower than those measured during the previous test phases, and the level never exceeds the 5 ppm emission goal.

On June 9-10th the engine UV sensor recorded an abrupt increase in catalyst outlet temperature. This temperature increase coincided with the pipeline natural gas scrubbers coming off-line for annual routine maintenance. As a consequence of the scrubbers being off-line, the concentration of heavy hydrocarbons (ethane, propane, hexane) in the fuel supply rose above the catalyst specification limits during this maintenance period. Once the scrubbers became operational again, the UV output returned to the normal range. All emission data were still within the target limits throughout this event.

	30 minute averages (ppm)			1 hour rolling averages (ppm)			3 hour rolling averages (ppm)		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
NO_x	0.7	1.1	1.6	0.7	1.1	1.5	0.8	1.1	1.5
CO	0.0	0.4	11.3	0.0	0.4	5.5	0.0	0.4	5.5
UHC	0.0	0.4	5.0	0.0	0.4	3.5	0.0	0.4	3.0

Table 6.4.2.1 -- Phase III emissions results

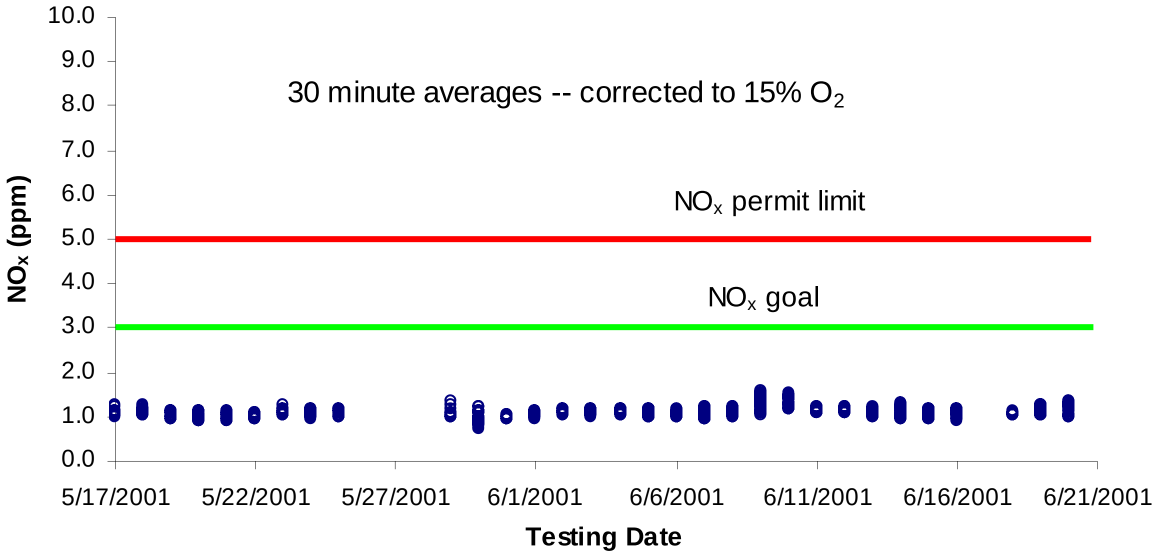


Figure 6.4.2.1 -- Phase III NO_x emission results (30 minute averages)

6.4.3 Phase III Hardware Condition

The combustor was removed from the engine after completion of an additional 772 RAMD hours (total RAMD hours 8128). The result of the visual inspection is detailed below.

- The BOZ was generally in good condition with some minor TBC spalling as seen from the previous builds
- The inner combustor liner was cracked near bolt flange. The primary tube/OD heat shield weld exhibited some minor cracking
- There was no evidence of TBC spalling off of the OD heat shield
- Swirler vane pack exhibited a crack in the vane fillet (Figure D1) that was subsequently repaired (Figure D2)
- The inlet catalyst foil (stage 1) was generally in good condition, however, there was a small 0.25 inch area that exhibited some minor deformation due to overheating.

The outlet catalyst foil (stage 2) showed a larger area of deformation. The likely cause of this deformation is the out-of-spec level of heavy hydrocarbons in the fuel measured on June 9-10th. A thorough investigation is underway to determine the exact cause of the deformation.

VII. Conclusions

- The RAMD engine program accumulated 8,128 on-grid operating hours utilizing a catalytic combustion system that was built/modified 4 times over the course of total operation. Reliability was calculated at 99.2%, which exceeded the goal of 98%. Availability was calculated at 91.2%, which fell short of the 96% goal. Maintainability was not calculated because the values for “average part failure rate” and “mean time to repair or replace the part” are not meaningful when design changes are made if a part fails. Likewise, Durability goals were not met due to the replacement of several key components during the course of the program. Based on the data collected that validate our model projections, the final combustor build can demonstrate the 8,000 hour-life goal.

- NO_x levels were quite low during the course of the entire test program and never exceeded 3.0 ppm (on a 30-minute average basis). All emission data are summarized at full-load design-point conditions. Emission values at part load, starting and shutdown may exceed the target levels.

- Overall average CO levels were well below the target goal of 5 ppm; however, on several occasions, especially early in the test program, the 30-minute average emission values exceeded the permit levels of 10 ppm. Changes in the control system implemented in subsequent test phases lowered the CO to acceptable levels.

- Overall average UHC levels were well below the target goal of 5 ppm, however, on a handful of occasions early in the test program, the 30-minute average emission values exceeded the target level of 5 ppm. Changes in the control system implemented in subsequent test phases lowered UHC emissions to levels below 5 ppm.

- The control system development activity produced new control logic to improve turndown, load shedding and emission control. It is clear that advanced controls development is critical to the success of the Xonon® combustion technology.

- The axial support structure had to be replaced after 4,000 hours due to poor durability. The Phase II testing incorporated a new axial support structure design developed outside of the PIER 1 program. The replacement of the axial support did not affect the Reliability or Availability of the Kawasaki Gas Turbine Generation system since the replacement occurred at a scheduled shutdown. Operating hours to date compared to the analytical model of the new support structure indicate the new support structure will exceed the durability goals of the combustion system.

- Both the Phase I and Phase II/III catalyst showed good durability up to 4,000 hours. However, it became clear that a new catalyst design being developed in a separate program at the CESI R&D center had aging characteristics that were better than the catalyst used during Phase I. The turbine-mounted combustor is the best place to assess and demonstrate long-term catalyst durability; so the original Phase I catalyst was replaced with the improved catalyst during build 5. The second-generation catalyst accumulated 4,000 hours while exhibiting good emission performance. Additional testing is currently underway to prove adequate emission performance up to the 8,000 hour performance target.

- The inclusion of an automated combustor by-pass system will quite likely be necessary to meet the turn-down emission requirements for future Xonon® applications. This will be particularly important for engine applications that operate a significant percentage of their duty cycle at part-load conditions and without the capacity to vary the engine air flow with compressor inlet guide vanes. The inclusion of a bypass system may be necessary in order to meet certification requirements.

- The overall project objective of demonstrating adequate RAMD performance has been met through a combination of demonstrated operating hours and modeling. The data collected during both phases of operation were used to validate our model projections (catalyst aging, axial support structure creep, liner temperatures for thermal cycle fatigue, etc.) to 8,000 hours of operation. The success of these efforts is evidenced by the decision of Kawasaki Heavy Industries to pursue commercialization of the Xonon system via their introduction of the M1A-13X gas turbine.

- The ISO heat rate for the Xonon-equipped engine at Silicon Valley Power (SVP) is approximately 15,700 BTU/kW-hr. It is important to note that the engine installed at SVP was purchased used and has a very poor performing engine (compressor efficiency was very marginal). The higher reported heat rate **cannot** be directly compared to the baseline Kawasaki gas turbine heat rate of 13,400 BTU/kW-hr. The heat rate of the engine at SVP has not been measured with a standard Kawasaki combustor.

Glossary

40 CFR	-	US Code of Federal Regulations Title 40 contains all Federal environmental regulations
Activity Test	-	Regular testing is conducted to assess the condition of the catalyst module. The test procedure involves incrementing the catalyst inlet temperature, and then varying the engine load to establish the envelope for operation within the emissions limits.
BMM	-	Bonded Metallic Monolith – the first-generation, honeycomb-like axial retainer
BOZ	-	Burn Out Zone – area where the combustion process is completed
CESI	-	Catalytica Energy Systems, Inc.
CEMS	-	Continuous Emissions Monitoring System
CGA	-	Cylinder Gas Audit, as defined by the CEMS QA/QC plan.
Corrected Emissions	-	Actual stack emission concentrations are corrected to 15% O_2 on a dry basis. The procedure for this correction is contained in 40 CFR 60.335.
CO	-	Carbon Monoxide
Daily Calibration	-	The CEMS undergoes an automatic calibration check each day at 6:00 AM to assess the zero and span drift. One or two 15 minute averages are lost each day because of the calibration.
DAS	-	Data Acquisition System
EGT	-	Exhaust Gas Temperature. This is the limiting parameter for gas turbine power. The turbine control system uses measured EGT to adjust the fuel schedule for operation at maximum design capacity under normal operating conditions
Event	-	Any abnormality in operation that warrants an explanation.
Load Step Test	-	Regular testing is conducted to assess the condition of the catalyst module. This test involves incrementing the engine load, and collecting data to assess the level of conversion in the catalyst module.
FID	-	Flame Ionization Detector
FOH	-	Forced Outage Hours – Hours when the unit is not available due to a condition beyond the control of the operator which requires that the condition be corrected before the end of the next weekend.
FOR	-	Forced Outage Rate
FSNL	-	Full Speed No Load - engine operating at 100% speed with no load
IR	-	Infra-Red
KHI	-	Kawasaki Heavy Industries
MTBO	-	Mean Time Between Overhaul
MTTR	-	Mean Time To Repair
Maximum Design Capacity	-	The maximum power that the turbine can produce at the prevailing ambient conditions (primarily temperature)

Normal Operation	-	Full load (over 98% of capacity) and steady state.
NO_x	-	Nitric Oxides
PH	-	Period Hours – Hours when the unit is operating in the configuration necessary to support the test objective
POH	-	Planned Outage Hours – Hours when the unit is not available for operation due to a shutdown that has been defined in advance
OD	-	Outer Diameter
QA/QC Plan	-	Quality Assurance / Quality Control plan for the emission monitoring system (40 CFR 60 Appendix F)
RAMD	-	Reliability, Availability, Maintainability, Durability
RATA	-	Relative Accuracy Test Audit is performed annually as defined by the CEMS QA/QC plan.
Rolling Average	-	Calculated each 30 minutes using the last 2 (for 1 hour) or 6 (for 3 hour) 30-minute data records. No rolling average is shown unless there is data for the entire averaging period.
RF	-	Reliability
RSH	-	Reserved Shutdown Hours – Hours when the unit is available for operation according to the test objective, but is currently shutdown by choice
MOH	-	Maintenance Outage Hours
SH	-	Service Hours
SVP	-	Silicon Valley Power
TBC	-	Thermal Barrier Coating
THC	-	Total Hydro-Carbons
UHC	-	Unburned Hydro-Carbons
Xonon®	-	CESI's flameless combustion system for NO_x control

Notes and References

[1] The proposed Section 40 CFR 51.165 paragraph (xxviii) amendment

Appendix A – Measurement Device Specifications

Range	0 to 25%
Response time	Less than 15 seconds to 90% at an inlet pressure of 3 psig

Table A1 -- O_2 Analyzer Specifications

Range	0 to 3000 ppm (low range scale 0-200 ppm)
Repeatability	± 5.0% scale
Noise	Less than 0.1% full scale
Response time	Less than 40 seconds to 95%
Linearity	Better than ±2%
Span drift	Less than ±0.5% of reading per 24 hours
Zero drift	Less than 0.1 ppm per 24 hours

Table A2 -- CO Analyzer Specifications

Range	0 to full scale sensitivity. Full scale sensitivity adjustable from 4 ppm to 1% methane.
Repeatability	1% of full scale for successive identical samples
Response time	90% of full scale in 0.6 seconds with sample bypass flow at 3 liters/minute
Stability	1% of full scale throughout ambient range of 32°F to 110°F
Linearity	Better than ±2%

Table A3 -- THC Analyzer Specifications

Range	0 to 200 ppm (low range scale 0-20 ppm)
Noise	0.1% full scale
Response time	Less than 30 seconds to 95% final value
Linearity	Better than ±1%
Span drift	Less than ±0.1% per °C; less than 1% of reading per 30 days
Zero drift	Less than ±1 ppb per °C; less than 1ppb of reading per 30 days

Table A4 -- NO_x Analyzer Specifications

Range	0 to 10%
Noise	Less than 0.1% full scale
Response time	Less than 10 seconds to 90%
Linearity	±1% full scale
Span drift	1% per 50°F
Zero drift	1% per 50°F

Table A5 -- CO_2 Analyzer Specifications

Appendix B -- RAMD Emissions Results

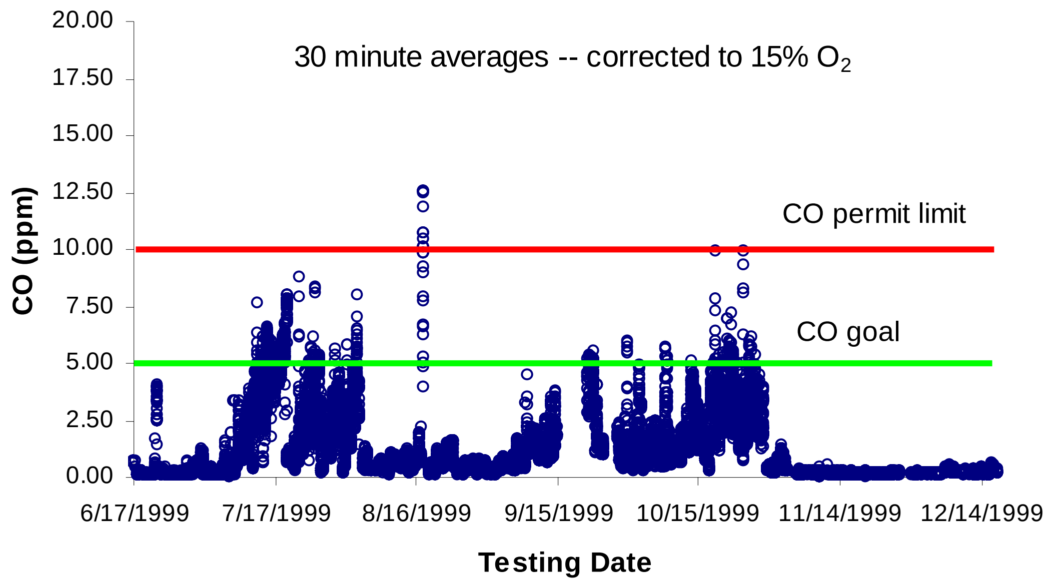


Figure B1 -- Phase I CO emissions results (30 minute averages)

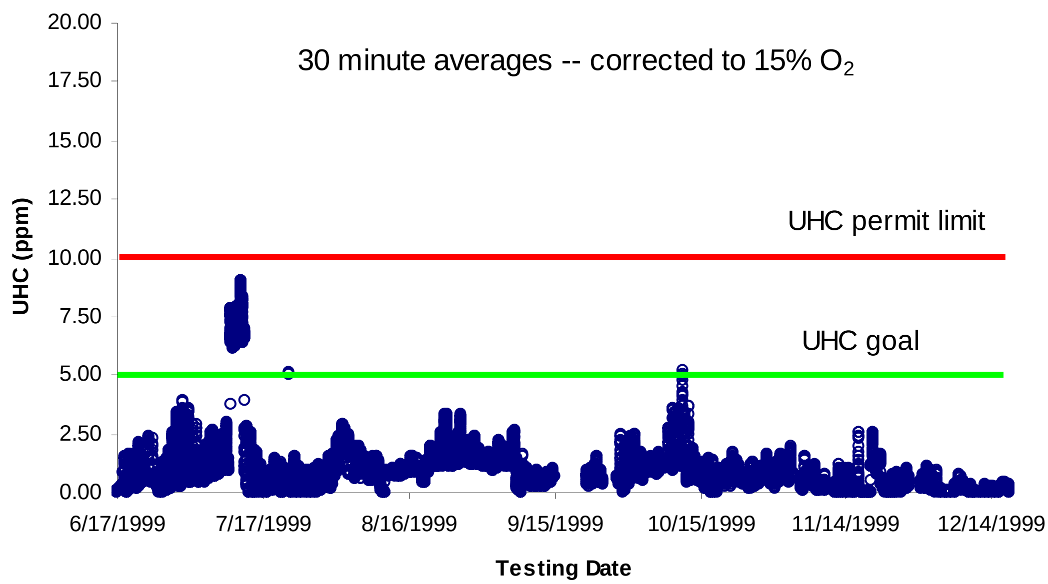


Figure B2 -- Phase I UHC emissions results (30 minute averages)

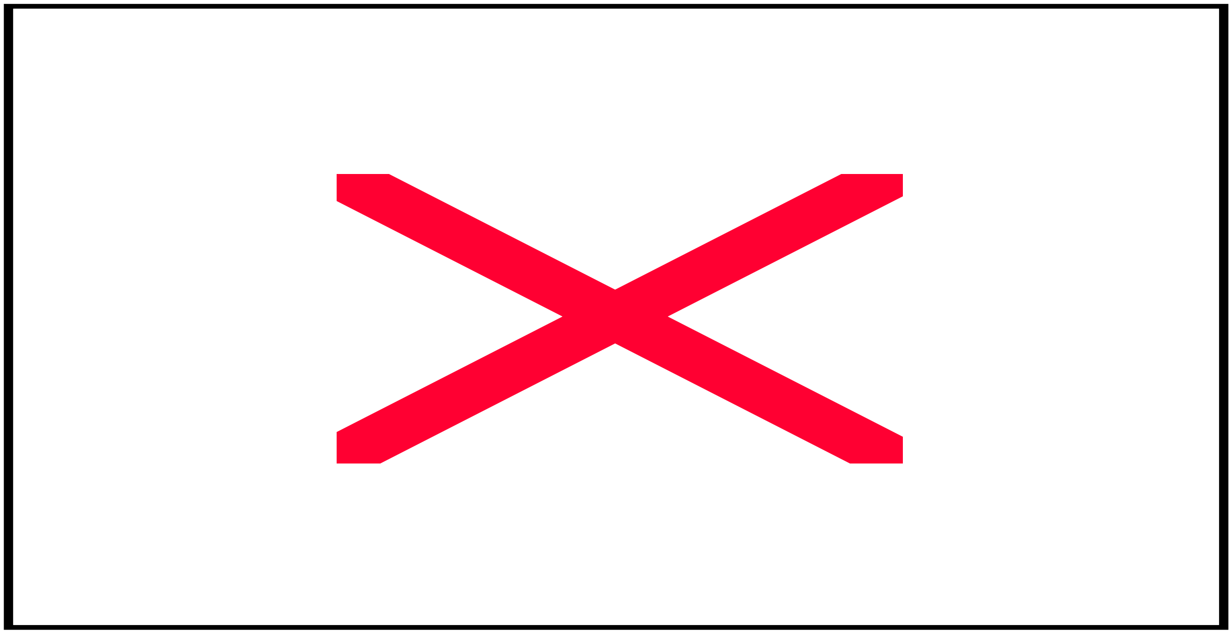
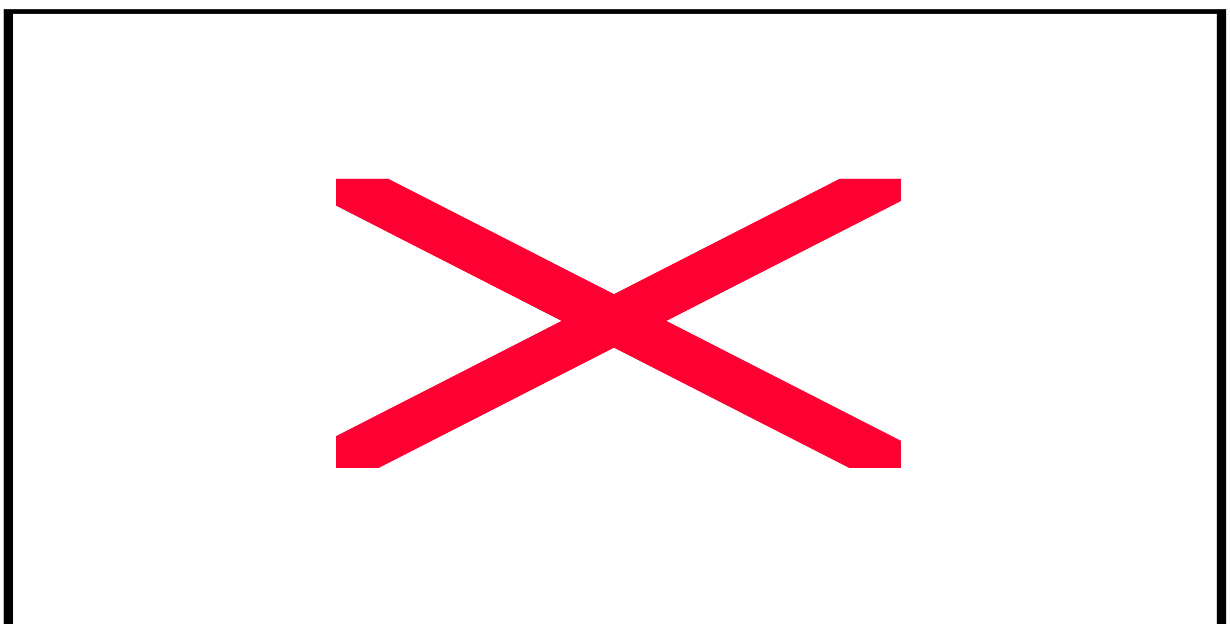


Figure B3 -- Phase II UHC emissions results (30 minute averages)



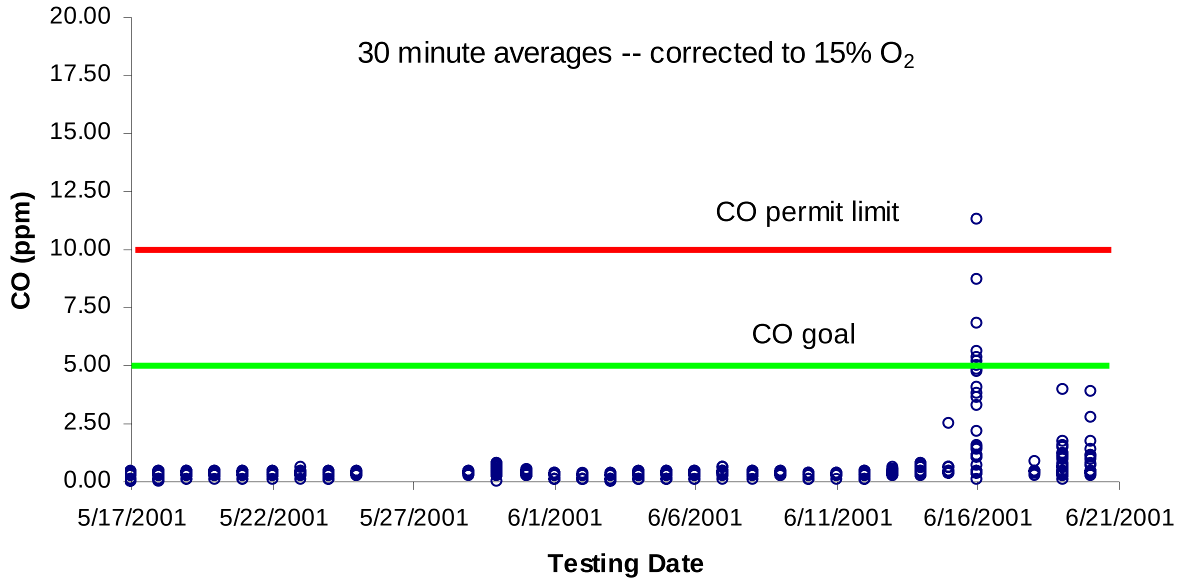


Figure B5 -- Phase III CO emissions results (30 minute averages)

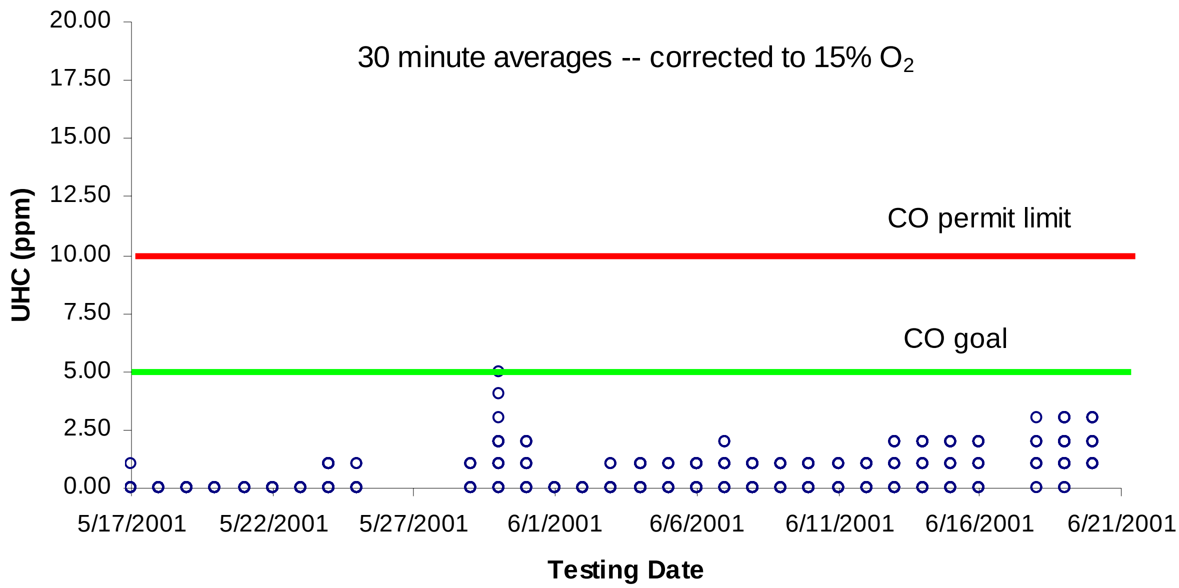


Figure B6 -- Phase III UHC emissions results (30 minute averages)

Appendix C – RAMD Phase I Hardware Photographs

Figure C1 – Xonon® 2.0 Catalyst module after 2064 hours of operation

Figure C2 -- Burnout zone (BOZ) after 2064 hours of operation

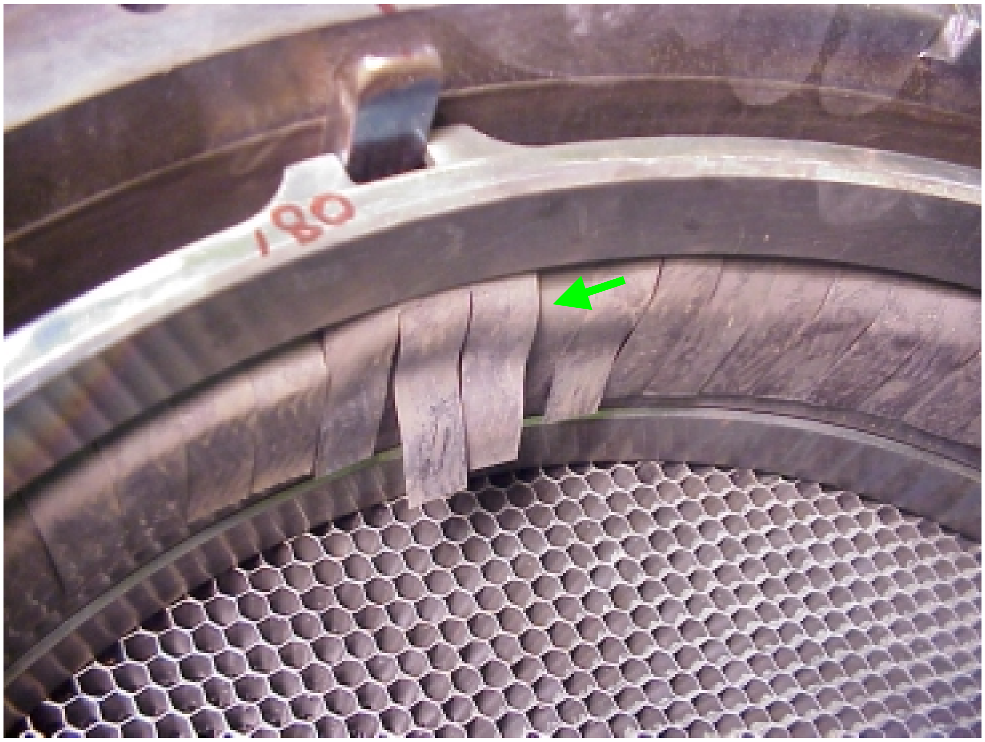


Figure C3 -- Finger seals showing deformation after 2064 hours of operation

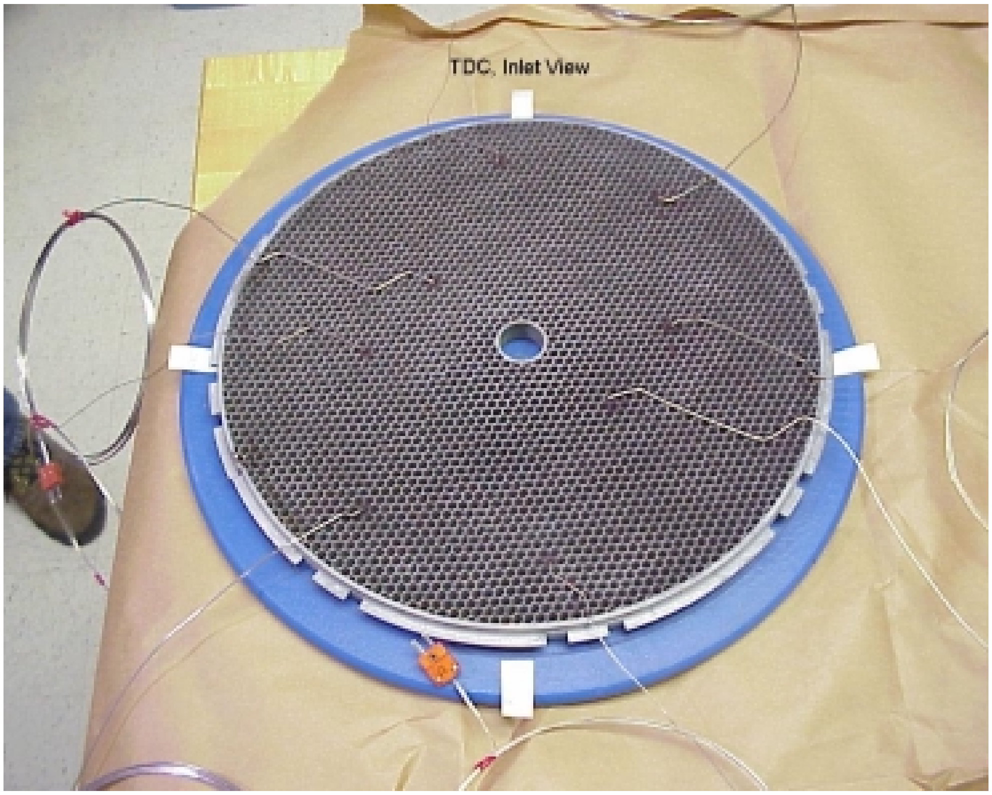


Figure C4 -- Reinstrumented outlet axial support structure (BMM) after 2064 hours of operation

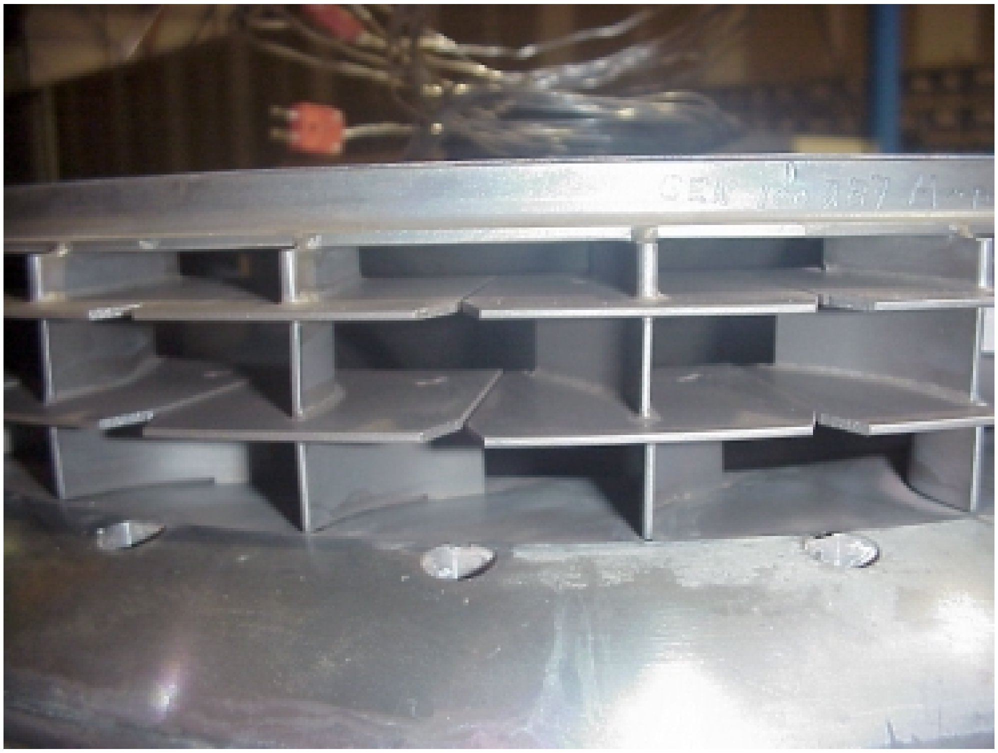


Figure C5 -- Swirler vane pack after 2064 hours of operation

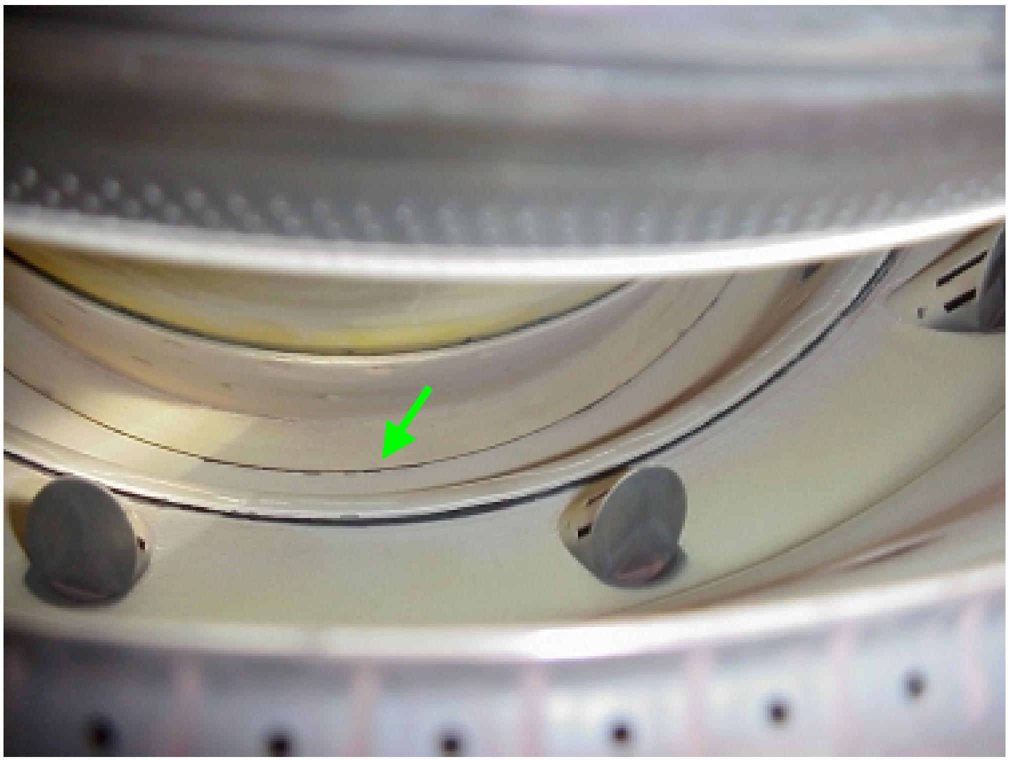


Figure C6 -- Closeup showing minor spalling on ID heat shield

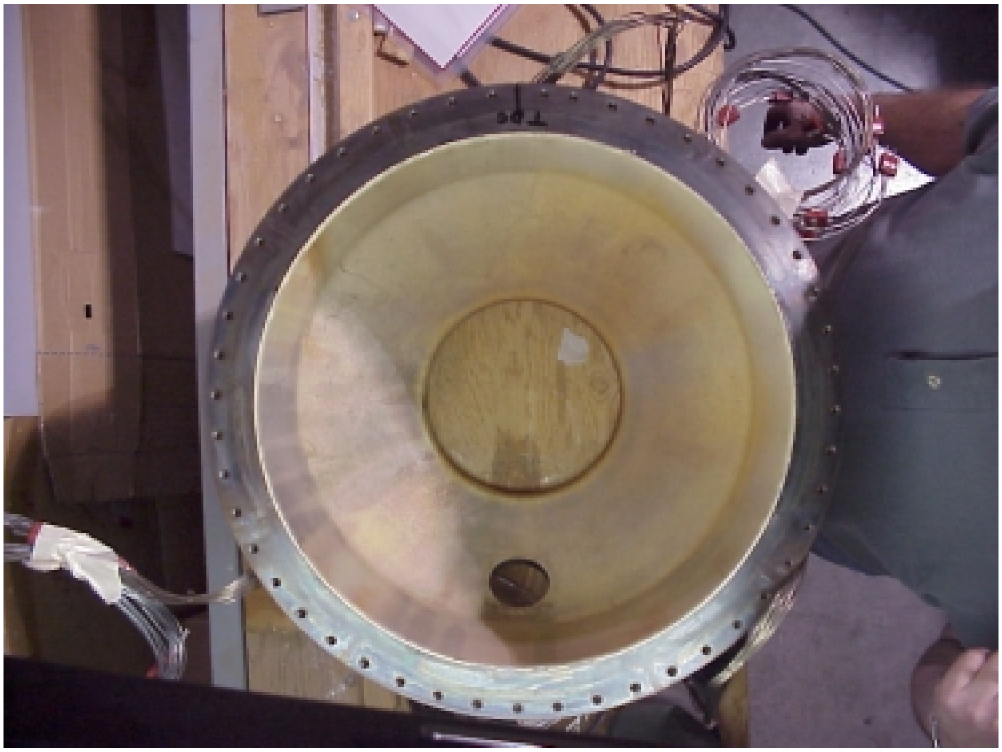


Figure C7 -- Burnout zone (BOZ) after 4128 hours of operation

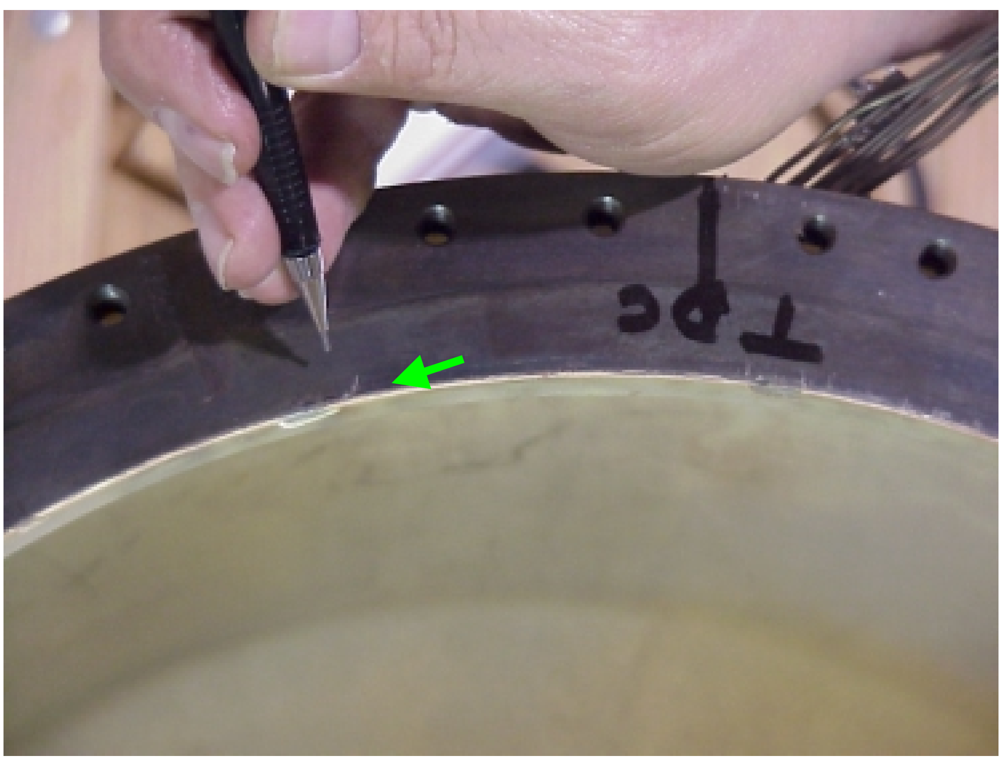


Figure C8 -- Burnout zone (BOZ) showing TBC flaking after 4128 hours of operation

Figure C9 -- Close up view of outlet axial support structure (BMM) after 4128 hours of operation showing cracking and deformation

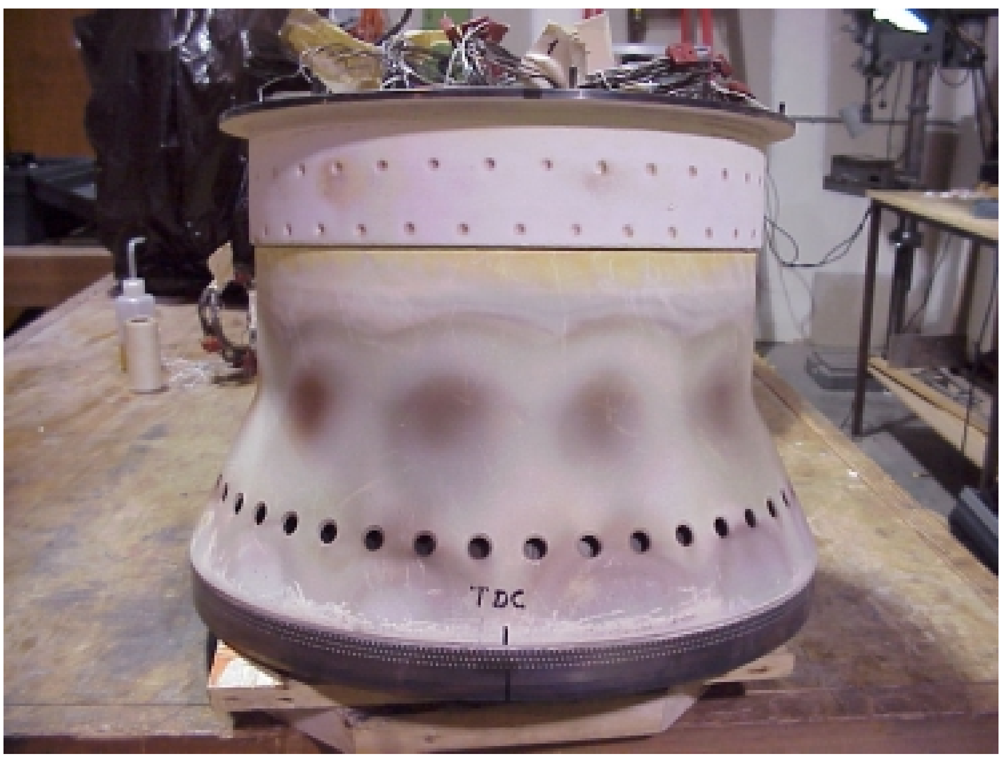


Figure C10 – Inner liner after 4128 hours of operation shows some discoloration

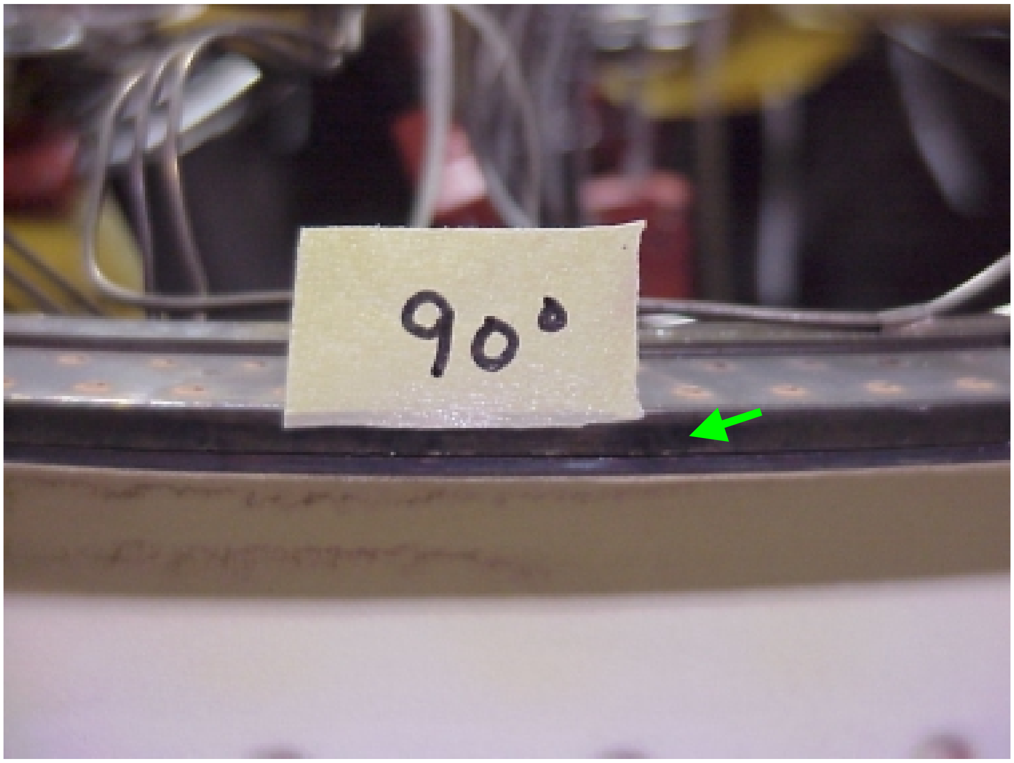


Figure C11 -- Inner liner crack after 4128 hours of operation

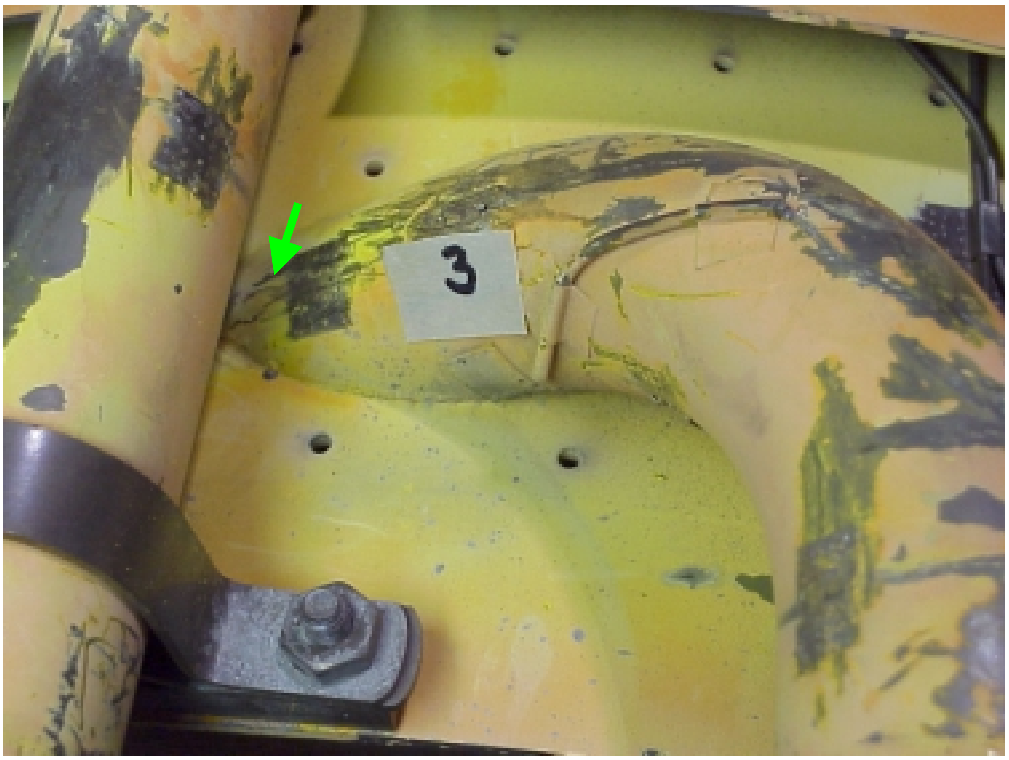


Figure C12 -- Primary duct crack after 4128 hours of operation

Appendix D – RAMD Phase III Hardware Photographs

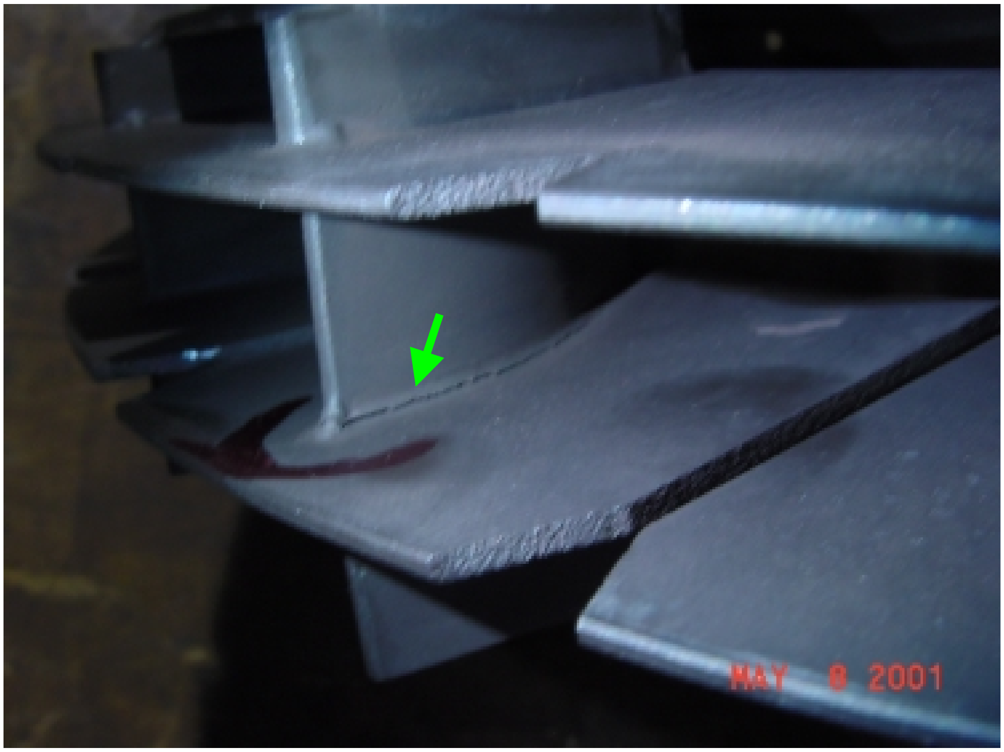


Figure D1 -- Close up showing premixer vane crack after 4000 hours of operation

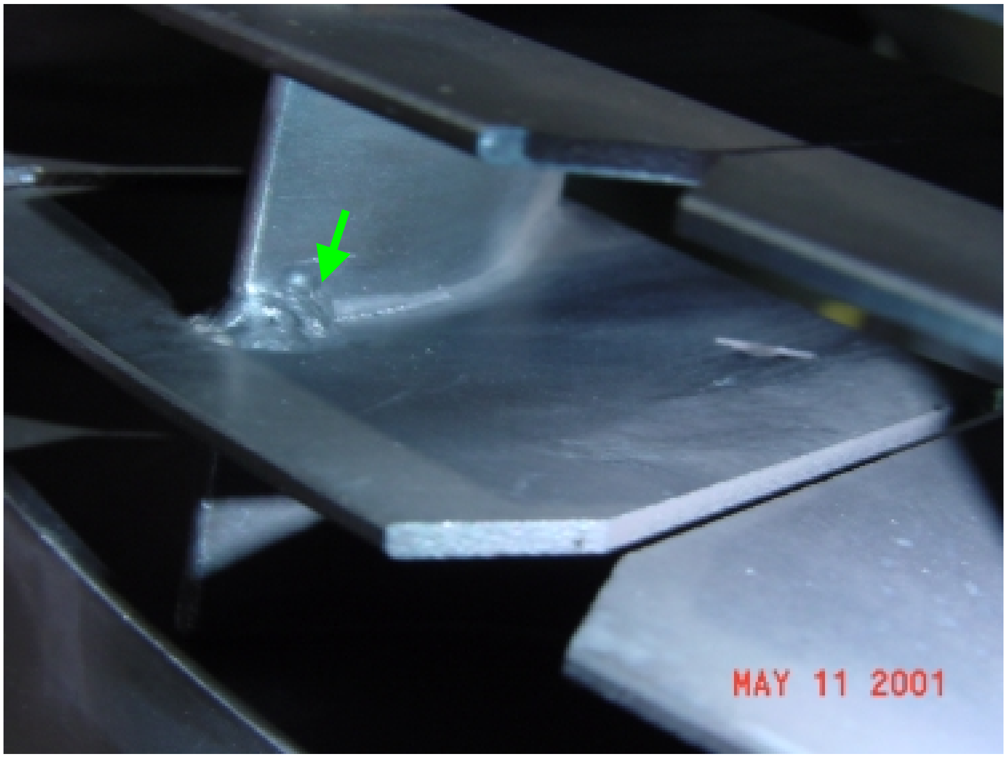


Figure D2 -- Close up showing premixer vane crack after repair

Appendix E – RAMD Event Codes

Each event was coded with a class, based on the quality and appropriateness of the data. All data collected is included in the data table, but Class 1 and Class 2 data is not included in the graph or the rolling averages. The various classes of data are colored in the data table as indicated below:

CLASS 1 - data is not a measurement of the exhaust stream gas
CLASS 2 - data is not typical due to non-standard operation
CLASS 3 - data is okay, but an event did occur

CODE WORD	CODE LETTER	DESCRIPTION	CLASS	% of Time
No Data	A	A data record is not available for this time period. A blank data record was generated to make the data set contiguous.	1	8.5%
Invalid Data	B	Indicated data is invalid, due to interruption of the data acquisition system (DAS). Invalid values are cleared from the data record.	1	0.0%
CEMS Malfunction	C	A malfunction occurred in either the turbine control system, data acquisition (DAS) or in the continuous emissions monitoring system (CEMS), causing incomplete or incorrect data collection. Emissions data is not included in the graph or rolling averages.	1	0.2%
CEMS Calibration	D	The continuous emissions monitoring system (CEMS) is undergoing a calibration check. The CEMS is programmed to perform a calibration check each day at approximately 6:00 AM to check for drift of the zero- and span- settings on each of the analyzers. Additional manual calibration checks are performed as necessary. During this brief period (15-20 minutes), the CEMS analyzers are taken offline from the turbine exhaust stream, and calibration gases are introduced into the probe. The measured species concentrations during this cycle do no represent the output of the gas turbine, and are not included in the graph or rolling averages. The span gas compositions are: NOx span = 20.0 ppm CO span = 30.0 ppm O2 span = 20.0% CO2 span = 7.5% UHC span = 100.0 ppm	1	2.6%
CEMS CGA	E	In accordance with CCSI's quality assurance / quality control (QA/QC) plan, a cylinder gas audit (CGA) is performed every three months to assess the accuracy of the CEMS analyzers. The CEMS probe is taken offline from the exhaust gas stream, and an EPA-certified test gas is introduced into the probe. Measured results are compared to the gas certification. Since the measured gas species are not from the turbine exhaust stream, emissions data is not included in the graph or rolling averages during the CGA audit.	1	0.0%

Startup	F	The engine is accelerating from a stop and ramping load to steady-state operation at maximum design capacity. Emissions data is not included in the graph or rolling averages during these startup periods.	2	0.4%
Shutdown	G	The engine is not operating due to either a planned or forced outage, and consequently not acting as an emissions source. Ambient emissions levels may be recorded, but emissions data is not included in the graph or rolling averages.	2	9.6%
Activity Testing	H	In order to support development of the Xonon® technology, and to help monitor and predict the performance of the catalyst module, a series of planned "activity tests" were scheduled throughout the operation of the engine. During these tests (typically 1-2 hrs), the preburner outlet temperature is set, and load is adjusted to identify the operation limits of the catalyst. By definition, this test will result in elevated emissions levels, and thus the emissions data is not included in the graph or rolling averages.	2	0.9%
Load Step Testing	I	In order to support development of the Xonon® technology, and to help monitor and predict the performance of the catalyst module, a series of planned "load step tests" are scheduled throughout the operation of the engine. During these tests (typically 1-2 hrs), the engine load is incremented and data is recorded to assess the level of "conversion" in the catalyst module. This test will result in elevated emissions levels, and thus the emissions data is not included in the graph or rolling averages.	2	0.5%
Development	J	In support of the development of the Xonon® technology, occasional engine tests are scheduled to investigate the response of the turbine and combustion system to potential changes in the hardware and/or control algorithms. The configuration and control utilized during these development tests is not representative of typical operation, and therefore emissions data are not included in the graph or rolling averages.	2	0.3%
Part Load	K	The engine is operating below 98% of its maximum design capacity, as determined by the exhaust gas temperature limit. Part load operation can be caused by a manual reduction of the load setpoint (e.g., during development testing), or automatic limiting in the control algorithm based on the gearbox mechanical limitation. The output power gearbox between the turbine and generator is undersized relative to the turbine capabilities, so low ambient temperatures which would otherwise allow the turbine to produce higher output loads result in the control system limiting operation to somewhat less than the maximum capability. Since 40 CFR 51.165(a)(1)(xxviii)(B)(2) indicates that the pollution control efficiency performance be verified with "(ii) Performance data collected at the maximum design	2	22.3%

		capacity of the emissions unit..", emissions data for operation under part load conditions is not included in the graph or rolling averages.		
Low Load	L	Indicated load is below 60% of the maximum design capacity of the turbine. For clarity, the load is not included in the graph or rolling averages.	2	0.0%
O2 Range	M	The recorded oxygen content is outside of the typical range for normal operation, indicating some otherwise unidentified perturbation. Exhaust stream O2 concentration should remain within a relatively narrow band defined by the chemistry of the combustion reaction (see Method 19) and the physical limitations of the combustor hardware. Measurements outside of this range indicate CEMS equipment malfunction, or calibration gas flowing to the CEMS probe. Emissions data under these conditions is suspect and therefore not included in the graph or rolling averages.	2	13.0%
Control Adjustment	N	The control system parameters were modified to adjust the operating line for the engine. The catalyst activity changes over time and varying ambient conditions, and periodic adjustments must be made to optimize the performance of the combustion system. The equipment configuration currently in use does not have provisions to make these adjustments automatically, and operating line changes are made in steps based on the observed trends. The resulting emissions measured subsequent to theses changes could exhibit a discontinuity relative to the data collected just prior to the change. This data is included in the graph and rolling averages.	3	0.3%
CEMS RATA	O	In accordance with CESI's quality assurance / quality control (QA/QC) plan, a Relative Accuracy Test Audit (RATA) is conducted annually to validate the accuracy of the CEMS. A separate, calibrated probe and analyzer is used in the exhaust stack, and samples are taken concurrently by both this system and the CEMS. The results are compared for agreement. Since the RATA uses a separate probe and analyzer, and since it is typically performed at load, the emissions data collected during these audits are included in the graph and rolling averages.	3	0.1%
Bad Temp	P	The recorded ambient temperature is not consistent with the surrounding data records, indicating a thermocouple malfunction. The temperature value was replaced with a simple average of the surrounding data sets. The ambient temperature is measured in the inlet duct of the engine, and during outages, this temperature is influenced by radiative heat transfer from the engine, causing the indicated temperature to rise upon shutdown. These temperature values are not adjusted for this presentation.	3	0.0%

Anomaly	Q	A discontinuity was observed in the data trend. Due to the dynamic response characteristics of the control system, and transient conditions in the fuel supply, occasional discontinuities are experienced which exhibit themselves as anomalies in the emissions data. Although this data is "real", the specific cause for the anomaly may not have been identified in all cases. This data is included in the graph and rolling averages.	3	1.8%
Exceedence	R	The control system has warning levels set for various operational parameters including emission levels. One or more of the exhaust gas species concentrations exceeded the warning level identified for that species. The DAS generates an alarm at preset limits, and a response team is prepared to take immediate action to address any potential exceedence. Further explanation for these events are provided as necessary in the event log entries. The data is included in the graph and rolling averages.	3	0.0%
Alarm	S	The control system DAS generated an alarm. The engine is equipped with extensive instrumentation to monitor and control various performance parameters. The majority of the defined alarms have no effect on emissions performance, and are not relevant to this data presentation.	3	1.1%

Table E1--RAMD event criteria